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EPA ALKALI SCRUBBING TEST FACILITY: SUMMARY OF TESTING THROUGH OCTOBER 1974

Michael Epstein

Bechtel, Incorporated

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EPA ALKALI SCRUBBING TEST FACILITY: SUMMARY OF TESTING THROUGH OCTOBER 1974

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EPA ALKALI SCRUBBING TEST FACILITY: SUMMARY OF TESTING THROUGH OCTOBER 1974

by

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16. ABSTRACT The report describes test results through 10/74 from a lime/limestone scrubbing test facility for removing SO2 and particulates from flue gases. The facility consists of three parallel scrubbers--a venturi/spray tower, a Turbulent Contact Absorber (TCA), and a marble-bed absorber--each able to treat a 10 Mw equivalent (30,000 acfm) of flue gas from a coal-fired boiler at TVA's Shawnee Station. Limestone factorial tests were conducted on all three scrubbers to determine the effects of the independent variables on SO2 and particulate removal. Limestone reliability verification tests were conducted on all three scrubbers to define regions for scale-free operation. Lime and limestone reliability tests were conducted on the venturi/spray tower and TCA systems, respectively, to demonstrate long-term reliability, primarily of the mist elimination systems. The TCA mist elimination system (a Koch Flexitray in series with a chevron mist eliminator) has remained essentially clean over a 1000 hour period at a superficial gas velocity of 8.6 ft/sec. A recent test of the spray tower mist elimination system (a chevron mist eliminator with provision for underside and topside washing) at a superficial gas velocity of 6.7 ft/sec indicated that long-term operability of this system may be expected.

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ABSTRACT

The report presents the test results from March 1972 to October 1974 on a prototype lime/limestone scrubbing test facility for removing SO_2 and particulates from flue gases. The facility consists of three parallel scrubbers -- a venturi/spray tower, a Turbulent Contact Absorber (TCA), and a Marble-Bed Absorber -- each treating 10 Mw equivalent (30,000 acfm) of flue gas from a coal-fired boiler at TVA's Shawnee Station. Limestone factorial tests to determine effects of independent variables on SO_2 and particulate removal, and limestone reliability verification tests to define regions for scale-free operation have been conducted on all three scrubbers. Lime and limestone reliability tests have been conducted on the venturi/spray tower and TCA systems, respectively, to demonstrate long-term reliability of the mist elimination systems. Mathematical models have been developed for predicting system performance. Test results have shown that scrubber internals can be kept relatively free of scale if the sulfate (gypsum) saturation of the scrubber liquor is kept below about 135 percent. The TCA mist elimination system consists of a Koch Flexitray in series with a chevron mist eliminator, both with underside wash. This system has been maintained essentially clean for over 1000 hours in a test at 8.6 ft/sec superficial velocity and 15 percent slurry solids concentration. The spray tower has a chevron mist eliminator with provision for underside and topside wash. At 6.7 ft/sec superficial velocity and 8 percent slurry solids concentration, neither intermittent nor continuous bottomside wash prevented solids buildup. A recent test has shown that a combination of intermittent topside and bottomside wash can keep the mist eliminator free of solids at the above conditions, but entrainment from the topside wash remains to be evaluated.

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Section 1

SUMMARY

This report describes a program by the Environmental Protection Agency (EPA) through its Office of Research and Development and Control Systems Laboratory to test prototype lime and limestone wet-scrubbing systems for removing sulfur dioxide and particulate matter from coal-fired boiler flue gases. The program is being conducted in a test facility integrated into the flue gas ductwork of a coal-fired boiler at the Tennessee Valley Authority (TVA) Shawnee Power Station, Paducah, Kentucky. Bechtel Corporation of San Francisco is the major contractor and test director, and TVA is the constructor and facility operator. This report presents the results of the testing program from its inception in March 1972 through October 1974. It includes mathematical models developed for predicting performance. An advanced testing program is continuing.

The test facility consists of three parallel scrubber systems:

- A venturi followed by a spray tower
- A Turbulent Contact Absorber (TCA)
- A Marble-Bed Absorber

Each system is capable of treating approximately 10 Mw equivalent (30,000 acfm[*] @ 300°F) of flue gas containing 1800 to 4000 ppm sulfur dioxide and 2 to 5 grains/scf of particulates.

The major goals of the test program have been:

- To characterize the effect of important process variables on sulfur dioxide and particulate removal.
- To develop mathematical models to allow scale-up to full-size scrubber facilities.
- To demonstrate long-term reliability.

The test program was divided into four test blocks:

(1) Air/water tests
(2) Sodium carbonate tests
(3) Limestone wet-scrubbing tests
(4) Lime wet-scrubbing tests

The air/water tests, which used air to simulate flue gas and water to simulate alkali slurry, were designed to determine the effects of the major independent variables on pressure drop for the three scrubbers in clean systems. Models for predicting pressure drop were fitted to the data.

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[*] Although it is the policy of the EPA to use the Metric System for quantitative descriptions, the British System is used in this report. Readers who are more accustomed to metric units are referred to the conversion table in Appendix A.

The sodium carbonate tests used water solutions of soda-ash to absorb SO_2 from flue gas and from a synthetic flue gas composed of air and SO_2. These tests were designed to determine the effects of independent variables on SO_2 removal for the three scrubbers under conditions where the gas-side mass transfer resistance is rate controlling and under conditions where both liquid and gas-side resistances are important. Models for predicting SO_2 removal were fitted to the soda-ash data.

The limestone wet-scrubbing tests were divided into three categories:

- Factorial tests
- Reliability verification tests
- Reliability tests

The limestone factorial tests were designed to determine the effects of the major independent variables on SO_2 and particulate removal for the three scrubbers. Models for predicting SO_2 removal were fitted to the data. The data showed that the percent of SO_2 removal was a function of liquor rate, scrubber internals (e.g., number of beds in the TCA), scrubber liquor pH, SO_2 inlet gas concentration, and scrubber liquor temperature. It showed that SO_2 removal was a function of gas rate in the spray tower and Marble-Bed scrubber, but varied only slightly with gas rate, if at all, in the venturi and TCA scrubbers.

The limestone reliability verification tests were designed to define regions for scale-free operation of the three scrubber systems. The scaling potential of scrubber internals was correlated to the degree of calcium sulfate (gypsum) saturation of the scrubber slurries.

The limestone reliability tests were designed to demonstrate long-term (2 to 5 month) operability. These tests were run on the TCA system only.

The lime wet-scrubbing tests were originally scheduled to be divided into the same three categories as the limestone wet-scrubbing tests. It was decided, however, to begin the lime testing with long-term reliability tests and to defer the factorial and reliability verification testing to a later data. Lime reliability tests were run on the venturi/spray tower system only.

Included in the overall test program were a particulate removal test program and an equipment evaluation program.

1.1 VENTURI/SPRAY TOWER

The adjustable throat venturi scrubber (manufactured by Chemical Construction Co.) was followed by a four-header spray tower for additional gas absorption capability. A chevron mist eliminator was used in the spray tower for demisting.

Typical scrubbing conditions during limestone factorial tests were:

> Venturi scrubber alone - 40 percent SO_2 removal at 25 gal/mcf liquid-to-gas ratio, 30,000 acfm (330°F) gas rate, and 6 to 12 inches H_2O pressure drop.
>
> Spray tower alone - 70 percent SO_2 removal at 50 gal/mcf liquid-to-gas ratio, 8 ft/sec gas velocity (30,000 acfm at 330°F), and 4 inches H_2O pressure drop.

Major problems alleviated during the venturi/spray tower lime reliability testing were:

- Scaling of scrubber internals
- Spray nozzle plugging

A continuing problem has been the scaling and plugging of the chevron mist eliminator.

The longest lime reliability test (Run 601-1A) on the venturi/spray tower system lasted 2150 hours (3 months). The test conditions were:

Spray tower gas velocity	6.7 ft/sec[*]
Venturi liquid-to-gas ratio	30 gal/mcf
Spray tower liquid-to-gas ratio	60 gal/mcf
Percent solids recirculated	8 percent
Effluent residence time	12 minutes
Scrubber inlet slurry pH (controlled)	8

In this test, SO_2 removal was 75 to 95 percent, lime utilization was approximately 90 percent, and the total pressure drop was about 12.5 inches H_2O, including 9 inches H_2O across the venturi. The run was terminated because of fan vibration and solids falling on the mist eliminator from the inlet ductwork which plugged up the mist eliminator.

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[*] In this report, all gas velocities and liquid-to-gas ratios are at scrubber operating conditions, i.e., saturated gas at scrubber temperature. With flue gas operation, the scrubber temperature is approximately 125°F. The gas velocities are all superficial velocities.

1.2 TCA SCRUBBER

The TCA scrubber (manufactured by Universal Oil Products) uses a mobile bed of low density plastic spheres that are retained between fixed grids. The TCA mist elimination system consisted of a wash tray in series with a chevron mist eliminator.

Typical scrubbing conditions during limestone factorial tests for a three-bed TCA were 90 percent SO_2 removal at 60 gal/mcf liquid-to-gas ratio, 10.5 ft/sec gas velocity, and 7 inches H_2O pressure drop.

Major problems alleviated during the TCA limestone testing were:

- Scaling of scrubber internals
- Scaling and plugging of mist elimination system (at 8.6 ft/sec gas velocity)
- Solids deposition at hot-gas/liquid interface
- Deterioration of wire mesh grids caused by vibrational wear at the points of contact

A continuing problem has been the operational life of the plastic spheres.

The most successful TCA limestone reliability test (Run 535-2A), still in progress at the end of October 1974, has accumulated nearly 1000 operating hours without significant accumulation of scale and solids on the scrubber internals and the mist elimination system. The test conditions for this run were:

Gas velocity	8.6 ft/sec
Liquid-to-gas ratio	73 gal/mcf
Percent solids recirculated	15 percent
Effluent residence time	15 minutes
Percent SO_2 removal (controlled)	85 percent

The scrubber inlet slurry pH was 5.7 to 6.0, the limestone utilization was approximately 65 percent, and the total pressure drop was about 6.5 inches H_2O. It is anticipated that a 3 month reliability run will be completed at these run conditions without scaling or plugging.

1.3 MARBLE-BED SCRUBBER

The Marble-Bed scrubber (supplied by Combustion Engineering Co.) uses a packed bed of 3/4-inch glass spheres (marbles). A turbulent layer of liquid and gas above the marble bed enhances mass transfer and particulate removal.

Typical scrubbing conditions during limestone factorial tests were 70 percent SO_2 removal at 33 gal/mcf liquid-to-gas ratio, 8.2 ft/sec gas velocity, and 11 inches H_2O pressure drop.

Major problems with the operation of the Marble-Bed scrubber were associated with the erosion of spray nozzles and the resultant plugging of the marble bed. Testing with the Marble-Bed scrubber was discontinued in July 1973.

1.4 MIST ELIMINATION

The most significant reliability problem encountered during the lime/limestone wet-scrubbing tests has been the tendency for mist eliminators to scale and/or plug. Hard scale formation is thought to be caused by the absorption of SO_2 into the process liquor adhering to the mist eliminator, oxidation in the liquor, and subsequent precipitation of calcium sulfate. Plugging results from slurry solids adhering to the mist eliminator surfaces. Additionally, these soft solids may act as sites for scale formation.

1.4.1 Wash Tray and Chevron Mist Eliminator in Series

The TCA mist elimination system consisted of a Koch Flexitray in series with a six-pass, closed-vane, stainless steel, chevron type mist eliminator during both the limestone reliability verification and reliability testing.

As of October 1974, a TCA run (Run 535-2A), operating at a superficial gas velocity of 8.6 ft/sec, has been in operation for almost 1000 hours without any significant scaling or plugging of the Koch tray or mist eliminator surfaces. For Run 535-2A, the underside of the Koch tray has been intermittently steam sparged (125 psig) for one minute every hour. The underside of the mist eliminator has been washed continuously with 15 gpm (0.3 gpm/ft^2) diluted clarified liquor, while the Koch tray has been irrigated with a combination of 8 gpm of clarified liquor plus the 15 gpm mist eliminator wash.

1.4.2 Chevron Mist Eliminator

A three-pass, open-vane, stainless steel, chevron type mist eliminator was used in the venturi/spray tower system during most of the testing to date.

In the venturi/spray tower system, operating at a superficial gas velocity of 6.6 ft/sec, there has been a continuing problem of scale formation on the top mist eliminator vanes. A variety of washing configurations have been tried in order to alleviate this problem.

Underside washing only, either continuously with low pressure water or intermittently with high pressure water, was unsuccessful in eliminating scale formation on the top vanes. A combination of intermittent high pressure topside and bottomside washing appears to have been successful in eliminating the scale accumulation on the upper mist eliminator vanes. However, operating experience in this configuration is limited, and entrainment of the topside wash water may be a problem.

1.5 SCALING AND SULFATE SATURATION

The limestone reliability test results with the TCA system have shown that scrubber internals can be kept relatively free of scale by maintaining sulfate (gypsum) saturation of the slurry liquor below about 135 percent at the scrubber inlet. This can be accomplished by proper selection of percent solids recirculated, effluent residence time, and liquid-to-gas ratio.

The data have shown that an effluent residence time of 10 minutes or more will maintain sulfate saturation below 135 percent in a limestone system at 15 weight percent solids recirculated and at a liquid-to-gas ratio of 64 to 80 gal/mcf. Under these test conditions, the bar-grids on the TCA were covered with less than 15 mils of sulfate scale after 1190 hours of operation during limestone reliability Run 526-2A.

Results from the lime reliability tests on the venturi/spray tower system have shown that the sulfate saturation of the scrubber inlet slurry liquor can be similarly correlated with percent solids recirculated, effluent residence time, and liquid-to-gas ratio. In addition, the lime testing has shown that the sulfate saturation is a strong function of flue gas inlet SO_2 concentration (SO_2 absorption rate). Also, the lime testing has shown that lime addition to the scrubber downcomer can substantially reduce the sulfate saturation, allowing for operation at reduced percent solids recirculated and/or residence time.

1.6 EQUIPMENT

1.6.1 TCA Internals

Until recently, sphere life has limited the long-term operability of the TCA scrubber. High-density polyethylene (HDPE) spheres eroded through and filled with slurry after about 2000 hours of operation. Thermoplastic rubber (TPR) spneres have been more successful, showing a weight loss of only 6 percent after 2500 hours. The TPR spheres tend to dimple, however, and can slip through the supporting bar-grids. This problem may be alleviated by respacing the bar-grids or using heavier spheres.

There has been no evidence of significant erosion of the bar-grids in the TCA after more than 5000 hours of operation. The original wire mesh grids deteriorated considerably during approximately 3000 hours of operation.

1.6.2 Spray Tower Nozzles

Initially, nozzle reliability in the spray tower was poor because of frequent plugging with foreign materials. Plugging was greatly reduced by installing dual strainers in the circulating slurry lines and by covering the hold tanks.

The original spiral tip Bete nozzles employed in the spray tower experienced severe erosion of the stainless steel tips after about 5400 hours in service. The original nozzles were replaced with stellite-tipped Bete nozzles, which have shown no measurable signs of erosion after approximately 5000 hours in service.

1.6.3 Hot-Gas/Liquid Interface

During limestone reliability verification testing, there was a continual problem of soft solids buildup at the hot-gas/liquid interface in the TCA and Marble-Bed scrubber inlet ducts, where the hot flue gas was cooled by slurry sprays to protect the rubber linings of the vessels.

The problem was solved by careful selection of proper size, location, and orientation of the slurry spray nozzles and by modification of the soot blower head to blow accumulated solids into the scrubber.

1.6.4 Reheaters

Fuel-oil-fired reheaters (from Hauck Manufacturing Co.) with external air supply and direct combustion in the flue gas stream were originally installed. They were difficult to ignite, had frequent flame-outs, and generated considerable soot. A fuel-oil-fired external combustion chamber (manufactured by Bloom Engineering Co.) was installed on the venturi/spray tower system in March 1974. This unit has performed satisfactorily with high reliability for over 4000 operating hours. An identical unit will be provided for the TCA.

1.6.5 Fans

Erosion, corrosion, pitting, scaling, etc. have been negligible on all three fans. Operation has been with 125°F flue gas reheat to give a fan inlet temperature of 250°F.

1.6.6 Pumps

The major pumps used in alkali slurry service at the Shawnee test facility are rubber lined variable-speed centrifugal pumps manufactured by Allen-Sherman-Hoff. In general, the rubber linings have shown excellent erosion-corrosion resistance and have remained in good condition. The original pumps had water-sealed packing, but were converted to air-purged packing during the boiler outage in February 1973 to help tighten the scrubber water balance.

1.6.7 Linings

The neoprene rubber linings in the spray tower, TCA, Marble-Bed, process water hold tanks, pumps, circulating slurry piping, and agitator blades have been found, generally, to be in excellent condition. Essentially no erosion or deterioration has been noted, except slight wear on some of the rubber-coated agitator blades. Hairline cracks have been noted in the glassflake lining on the effluent hold tanks and clarifiers. However, the cracks did not appear to penetrate the entire thickness of the lining.

1.6.8 Waste Solids Handling Equipment

Separate clarifiers to concentrate slurry discharge are provided for each scrubber system. A rotary drum vacuum filter and a horizontal solid bowl centrifuge are common to the three systems.

The venturi/spray tower and Marble-Bed systems have 20-foot diameter clarifiers while the TCA clarifier is 30 feet in diameter. The TCA clarifier has operated satisfactorily, with underflow solids concentrations approaching 40 wt %. The smaller clarifiers are undersized, averaging about 25 wt % underflow solids concentration. To maintain a tight water balance for closed liquor loop operation, the smaller units must be used in series with the filter or centrifuge.

The rotary drum vacuum filter manufactured by Ametek has produced a filter cake containing 50 to 55 and 45 to 50 wt % solids from limestone and lime slurries, respectively. Filter operation has been significantly hampered by the short life of the filter cloth which has been generally below 260 hours.

The continuous solid-bowl centrifuge manufactured by Bird Machine Co., operating either directly on scrubber slurry bleed or in series with a clarifier, has produced cake solids of 55 to 65 wt % in limestone service with centrate solids averaging 0.5 to 1.0 wt %. A major repair of the unit was necessary after about 1400 hours of operation due to severe erosion.

1.6.9 Instruments

The Du Pont Model 400 UV sulfur dioxide analyzers have operated essentially trouble-free following modification of the sampling systems to reduce leaking and plugging.

Two types of pH meters have been used in slurry service: (1) Uniloc in-line flow-through meters and (2) Uniloc submersible electrode meters. Performance of the in-line flow-through meters has been unsatisfactory because of erosion and failure of the glass cells and plugging of sample lines. The submersible electrode meters have been free of such problems during approximately 9000 hours of operation.

Three types of density meters have been used in slurry service: (1) Ohmart radiation meters, (2) differential pressure (bubbling tube) meters, and (3) Dynatrol vibrating U-tube meters. The radiation meter has a continual calibration shift which is accelerated by scale formation. The gas line on the differential pressure meter plugs frequently but the meter is accurate when clean. Performance of the vibrating U-tube meters has been excellent with few in-service problems.

Slurry flow rates have been measured by Foxboro magnetic flow meters and by both orifice and Annubar differential pressure meters. Performance of the magnetic flowmeters and orifice flowmeters has generally been adequate. Annubar meters have plugged frequently and required excessive maintenance.

Operating experience with control valves in slurry service has generally been unsatisfactory. Severe erosion and frequent plugging has been experienced with stainless steel plug valves, stainless steel globe valves, and rubber pinch valves. Trouble-free flow control has been achieved only with variable-speed pumps.

1.7 PARTICULATE REMOVAL

EPA has conducted overall particulate removal tests on all three scrubber systems and particulate distribution tests on the TCA system. TVA personnel have made additional particulate removal measurements at various times on the venturi/spray tower and TCA systems.

In general, measured particulate removal efficiencies on the three scrubber systems have been higher than efficiencies predicted from impaction theory. The enhanced efficiencies are probably the result of condensation of water vapor from the flue gas on the solid particles during the scrubbing operation.

Particulate loadings in the flue gas entering the scrubbers averaged about 2 to 5 grains/scf. Mass mean diameter of the particles in the inlet flue gas averaged about 20 to 30 microns.

For the Chemco venturi alone, measured particulate removal efficiency averaged 99.6 percent at 9 inches H_2O and 12 to 25 gal/mcf.

For the spray tower alone, measured removal efficiency averaged 98.4 percent at 4 ft/sec gas velocity (0.5 inch H_2O) and 37 gal/mcf.

For the venturi and spray tower operating simultaneously, measured removal efficiency averaged 99.1 percent with the venturi at 9 inches H_2O and 30 gal/mcf and the spray tower at 6.6 ft/sec gas velocity (2 to 3 inches H_2O) and 61 gal/mcf.

For the TCA with 3 beds and 5 inches of spheres per bed, measured removal efficiency ranged from 99.2 percent at 8.6 ft/sec gas velocity (5.6 inches H_2O) and 36 gal/mcf to 99.8 percent at 10.7 ft/sec gas velocity (9.8 inches H_2O) and 72 gal/mcf. Mass mean diameter of the particles in the outlet gas averaged 0.5 to 0.75 microns.

For the TCA with 5 grids and no spheres, measured removal efficiency averaged 99.3 percent at 8.3 ft/sec gas velocity (4 to 7 inches H_2O) and 46 gal/mcf.

For the Marble-Bed, measured removal efficiency averaged 99.1 percent at 5.5 ft/sec gas velocity (12 inches H_2O) and 51 gal/mcf.

Section 2

INTRODUCTION

In June 1968, the Environmental Protection Agency (EPA), through its Office of Research and Development (OR&D) and Control Systems Laboratory, initiated a three phase program to test a prototype lime and limestone wet-scrubbing system for removing sulfur dioxide and particulates from flue gases. The system is integrated into the flue gas ductwork of a coal-fired boiler at the Tennessee Valley Authority (TVA) Shawnee Power Station, Paducah, Kentucky. Bechtel Corporation of San Francisco is the major contractor and test director, and TVA is the constructor and facility operator.

The major goals of the test program were: (1) to characterize as completely as possible the effect of important process variables on sulfur dioxide and particulate removal, (2) to develop mathematical models to allow economic scale-up of attractive operating configurations to full-size scrubber facilities, and (3) to perform long-term reliability testing.

Phase I of the test program consisted of preliminary engineering, equipment evaluation, and site selection. Phase II involved the detailed design and construction of the facility, and the development of the test plan and mathematical models for predicting system performance. Phase III, the testing portion of the program, began in March 1972.

The following sequential test blocks were defined for the program:

(1) Air/water tests

(2) Sodium carbonate tests

(3) Limestone wet-scrubbing tests

(4) Lime wet-scrubbing tests

The limestone and lime wet-scrubbing test blocks were divided into three general categories: (1) short-term (less than 1 day) factorial tests, (2) longer term (about 3 weeks) reliability verification tests, and (3) long-term (2 to 5 months) reliability tests. The object of the factorial tests was to determine the effect of independent variables (e.g., gas rate) on SO_2 removal for the scrubber systems. The primary objective of the reliability verification tests was to define regions for reliable (e.g., scale-free) operation of the scrubber systems. The object of the reliability tests was to determine the long-term operating reliability for the scrubber systems and to develop definitive process economics data and scale-up factors. The test program has been described in detail in References 1 and 2.

This report presents the results of testing at the Shawnee facility from March 1972 to October 1974 (Phase III) and the mathematical models developed for predicting system performance (Phase II).

In June 1974, the EPA initiated a two-year Advanced Test Program at the Shawnee facility. The advanced program will involve, primarily, limestone testing on the TCA system and lime testing on the venturi/spray tower system. The major goals of the advanced program are:

- To continue long-term testing with emphasis on the demonstration of reliable mist eliminator operation.
- To investigate advanced process and equipment design variations (e.g., operation with process slurry unsaturated with respect to gypsum) for the improvement of system reliability and process economics.
- To perform long-term (2 to 5 months) reliability testing on advanced process and equipment design variations.
- To determine the practical upper limits of sulfur dioxide removal efficiency.
- To evaluate system performance and reliability without fly ash in the flue gas.
- To evaluate process variations for substantial increase in limestone utilization with corresponding minimization of sludge production.
- To evaluate the effectiveness of three commercially offered sludge fixation processes and of untreated sludge disposal.
- To develop a computer program, in conjunction with TVA, for the design and cost comparison of full-scale limestone and lime systems.

The Advanced Test Program is described in detail in Reference 3. The Advanced Test Program Manual, although not prepared for widespread distribution, is available upon request from Bechtel Corporation. The first interim report for the Advanced Test Program will be issued by the EPA in late 1975.

Section 3

TEST FACILITY

The test facility consists of three parallel scrubber systems, each with its own slurry handling system. Scrubbers are of prototype size, each capable of treating approximately 30,000 acfm of flue gas from the TVA Shawnee coal-fired boiler No. 10. This gas rate is the equivalent of approximately 10 Mw of power plant generation capacity. The equipment selected was sized for minimum cost consistent with the ability to extrapolate results to commercial scale.

Boiler No. 10 burns a high-sulfur bituminous coal which produces SO_2 concentrations of 1800 to 4000 ppm and inlet particulate loadings of 2 to 5 grains/scf in the flue gas.

3.1 SCRUBBER SELECTION

The major criterion for scrubber selection was the potentiality for removing both sulfur dioxide and particulates at high efficiencies (sulfur dioxide removal greater than 80 percent and particulate removal greater than 99 percent). Other criteria considered in the selection of the scrubbers were:

- Ability to handle slurries without plugging or excessive scaling
- Reasonable cost and maintenance

- Ease of control
- Reasonable pressure drop

Based on the information available in the literature, the following scrubbers were selected:

(1) Venturi followed by a spray tower
(2) Turbulent Contract Absorber (TCA)
(3) Marble-Bed Absorber

The venturi scrubber (manufactured by Chemical Construction Co.) contains an adjustable throat that permits control of pressure drop over a wide range of flow conditions. Although a venturi is an effective particulate removal device, it has limited capability for gas absorption in lime/limestone wet scrubbing systems because of low slurry residence time. For this reason the spray tower was included for additional absorption capability.

The TCA scrubber (manufactured by Universal Oil Products and described in Reference 4) utilizes a fluidized bed of 1 1/2-inch-diameter, 5-gram hollow spheres which are free to move between retaining grids.

The Marble-Bed scrubber (supplied by Combustion Engineering Co. and described in Reference 5) utilizes a packing of 3/4-inch glass spheres (marbles). A "turbulent layer" of liquid and gas above the glass spheres enhances mass transfer and particulate removal.

Figures 3-1, 3-2, and 3-3 (drawn roughly to scale) show the three scrubber systems along with the mist elimination systems selected for

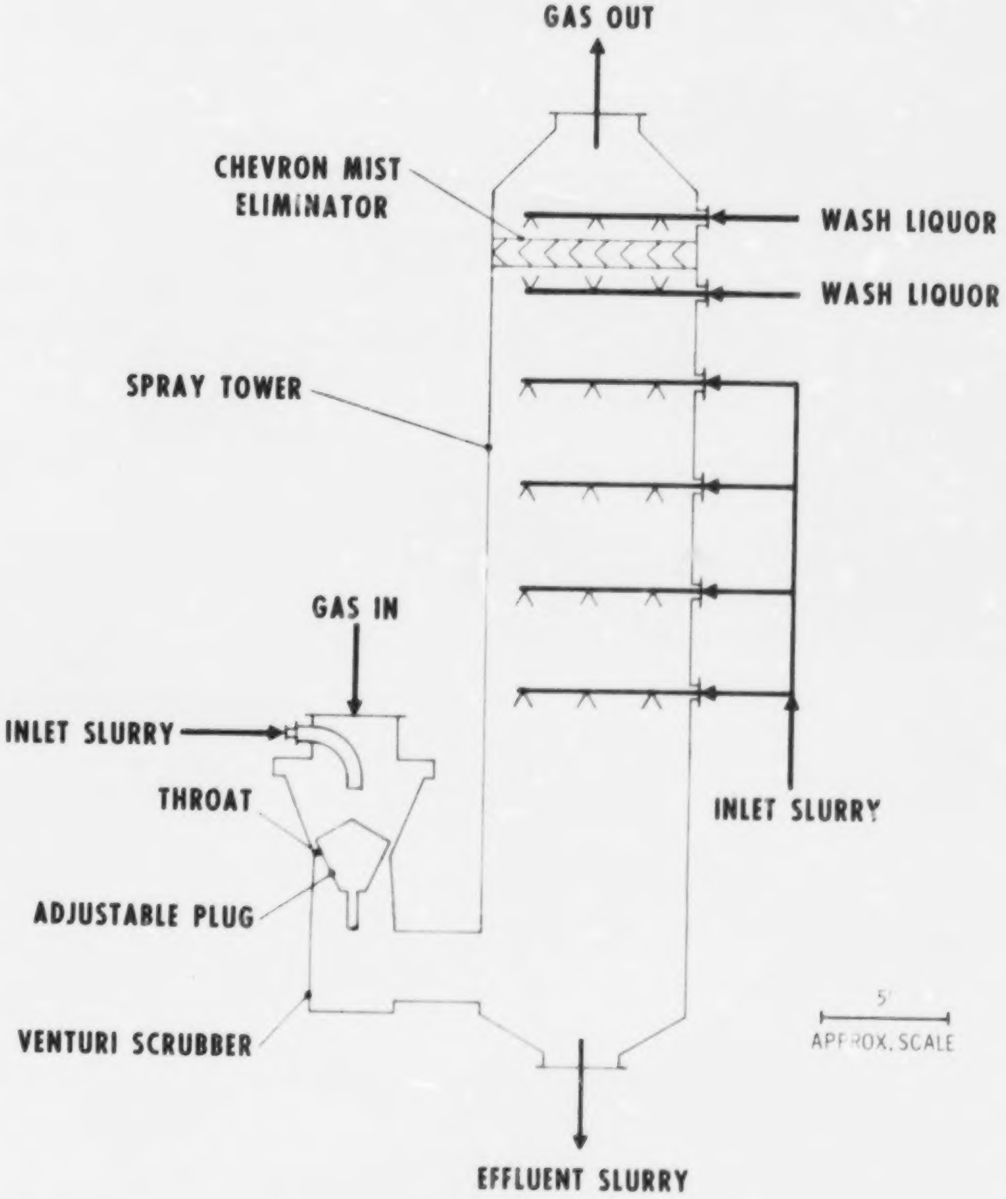

Figure 3-1. Schematic of Venturi Scrubber and Spray Tower

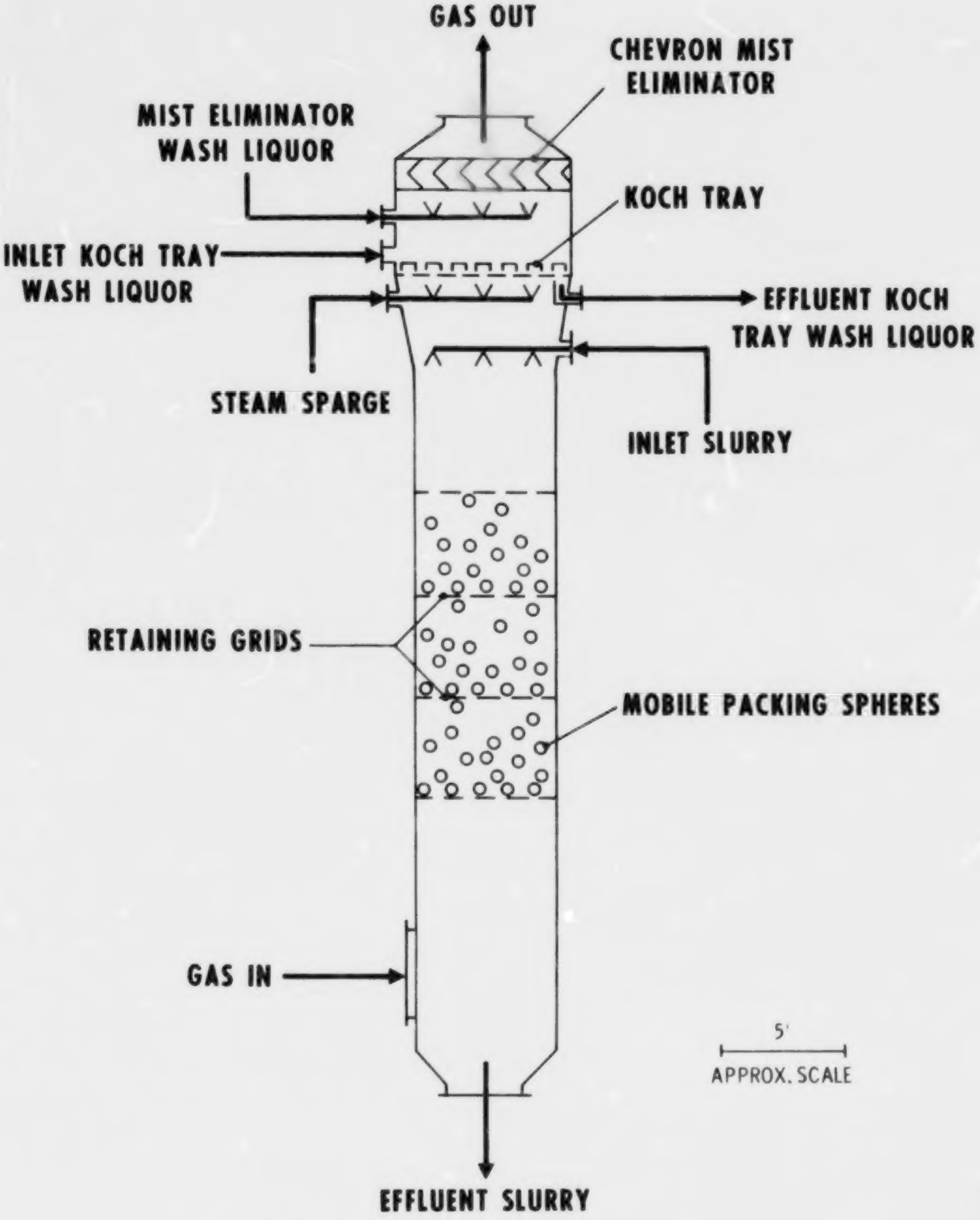

Figure 3-2. Schematic of Three-Bed TCA Scrubber

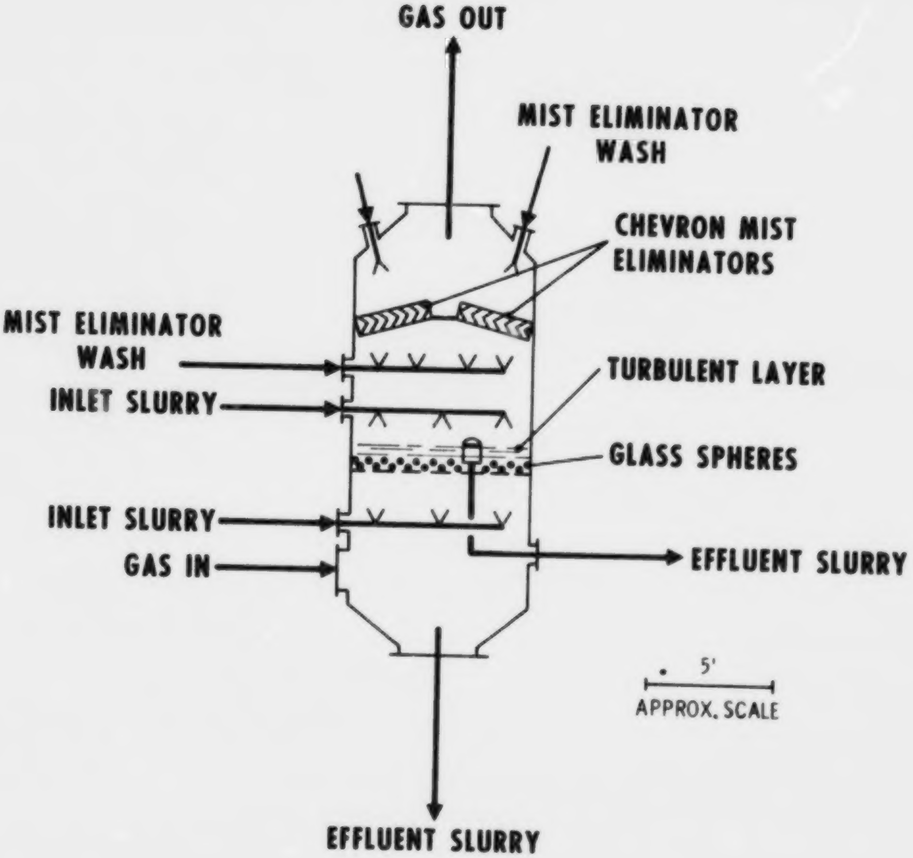

Figure 3-3. Schematic of Marble-Bed Scrubber

de-entraining slurry in the exit gas streams. The chevron mist eliminators used during the testing on the three scrubber systems are depicted, to scale, in Figure 3-4. The cross-sectional areas of the spray tower, TCA, and Marble-Bed scrubbers are 50, 32, and 49 ft^2, respectively.

3.2 SYSTEM DESCRIPTION

The Shawnee test facility contains five major areas:

(1) The scrubber area (including tanks and pumps)

(2) The operations building area (including laboratory area, electrical gear, centrifuge, and filter)

(3) The thickener area (including pumps and tanks)

(4) The utility area (including air compressors, air dryer, limestone storage silos, mix tanks, gravimetric feeder, and pumps)

(5) The pond area

The test facility has been designed so that a varied number of different scrubber internals and piping configurations can be used with each scrubber system. For example, the TCA scrubber can be operated with one, two, or three beds of spheres or with only the support grids. Solid separation can be achieved with a clarifier alone or with a clarifier in combination with a filter or a centrifuge.

Some typical configurations for limestone testing with the venturi/spray tower, TCA, and Marble-Bed scrubber systems are shown schematically in Figures 3-5, 3-6, and 3-7, respectively. Such process details as flue gas saturation (humidification) sprays are not shown.

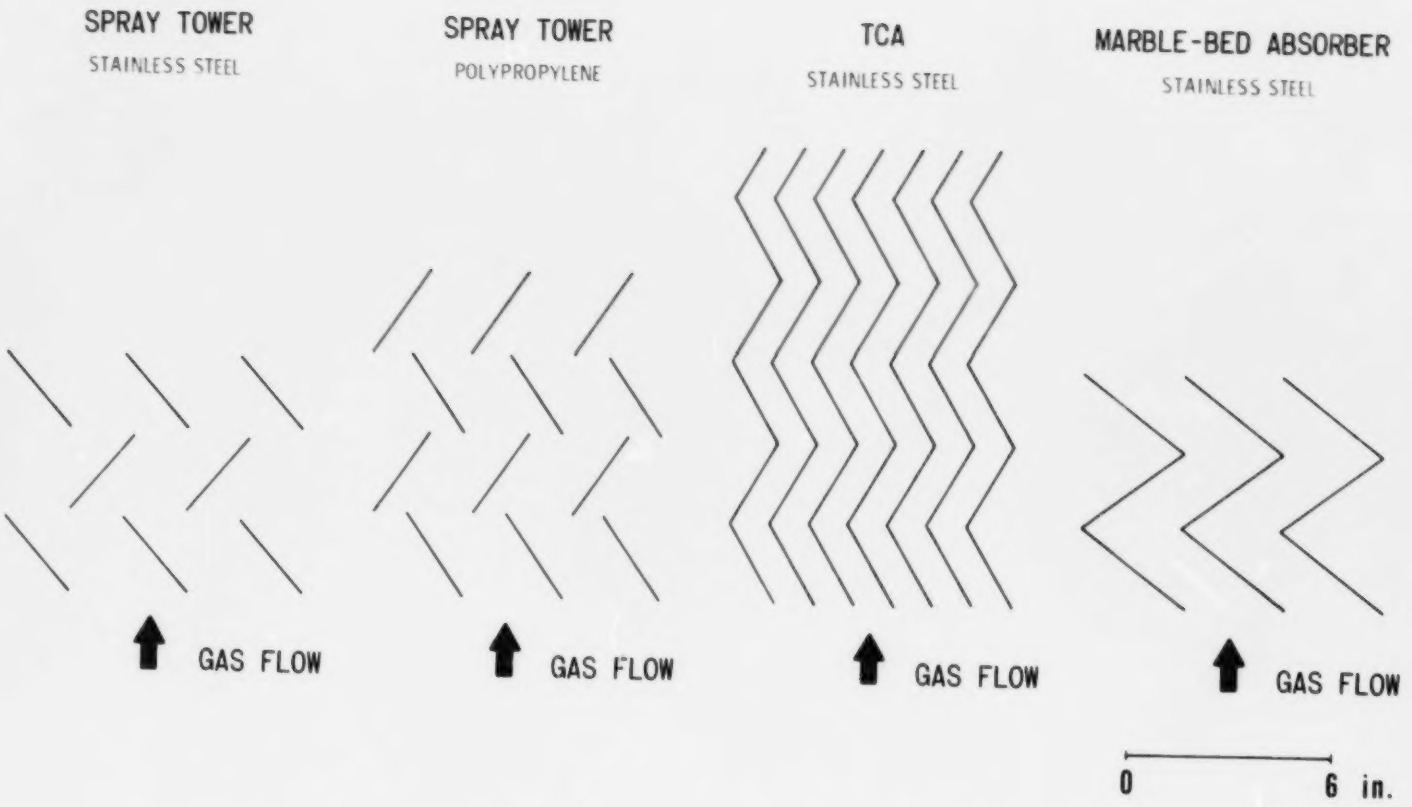

Figure 3-4. Test Facility Mist Eliminator Configurations

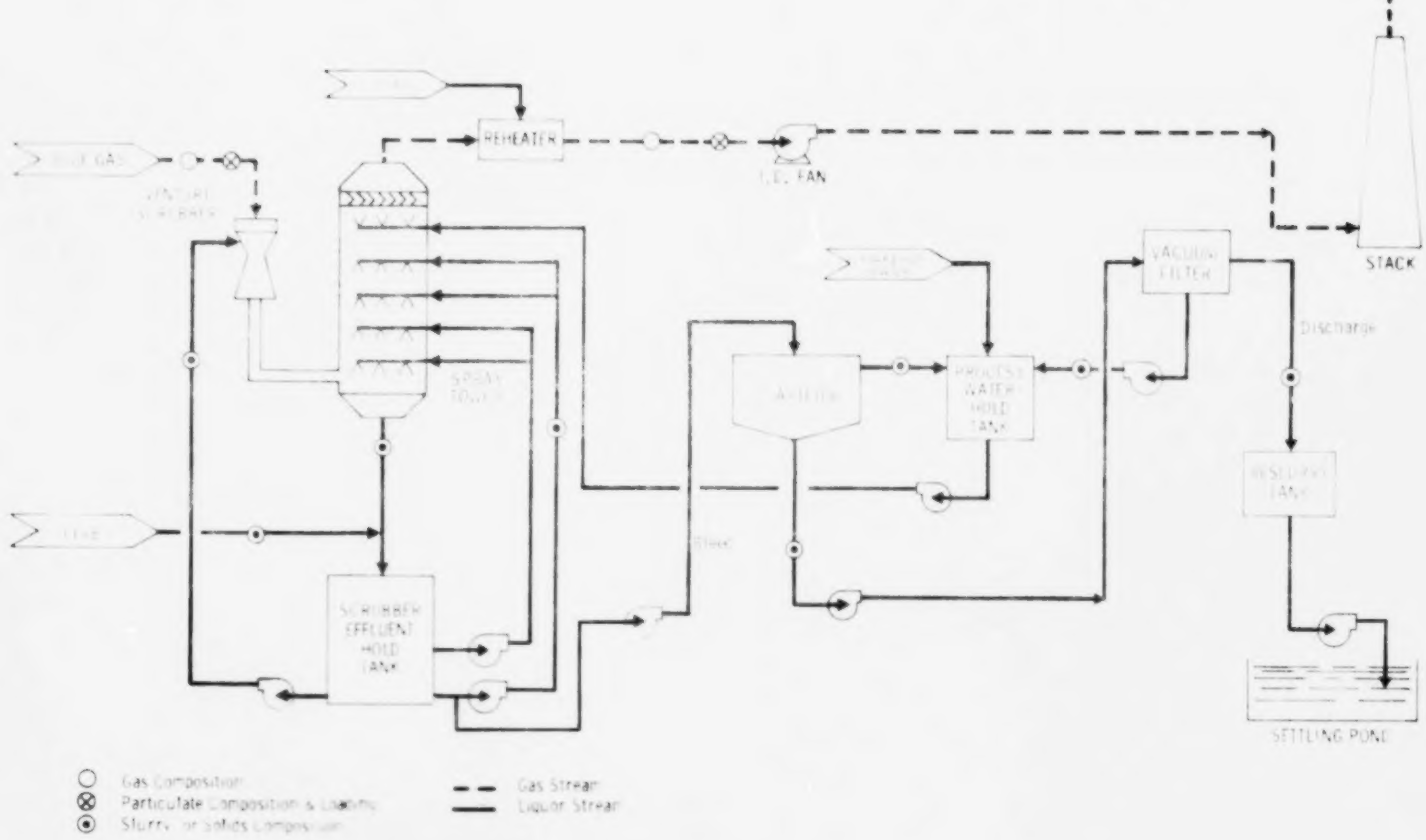

Figure 3-5. Typical Process Flow Diagram for Venturi/Spray Tower System

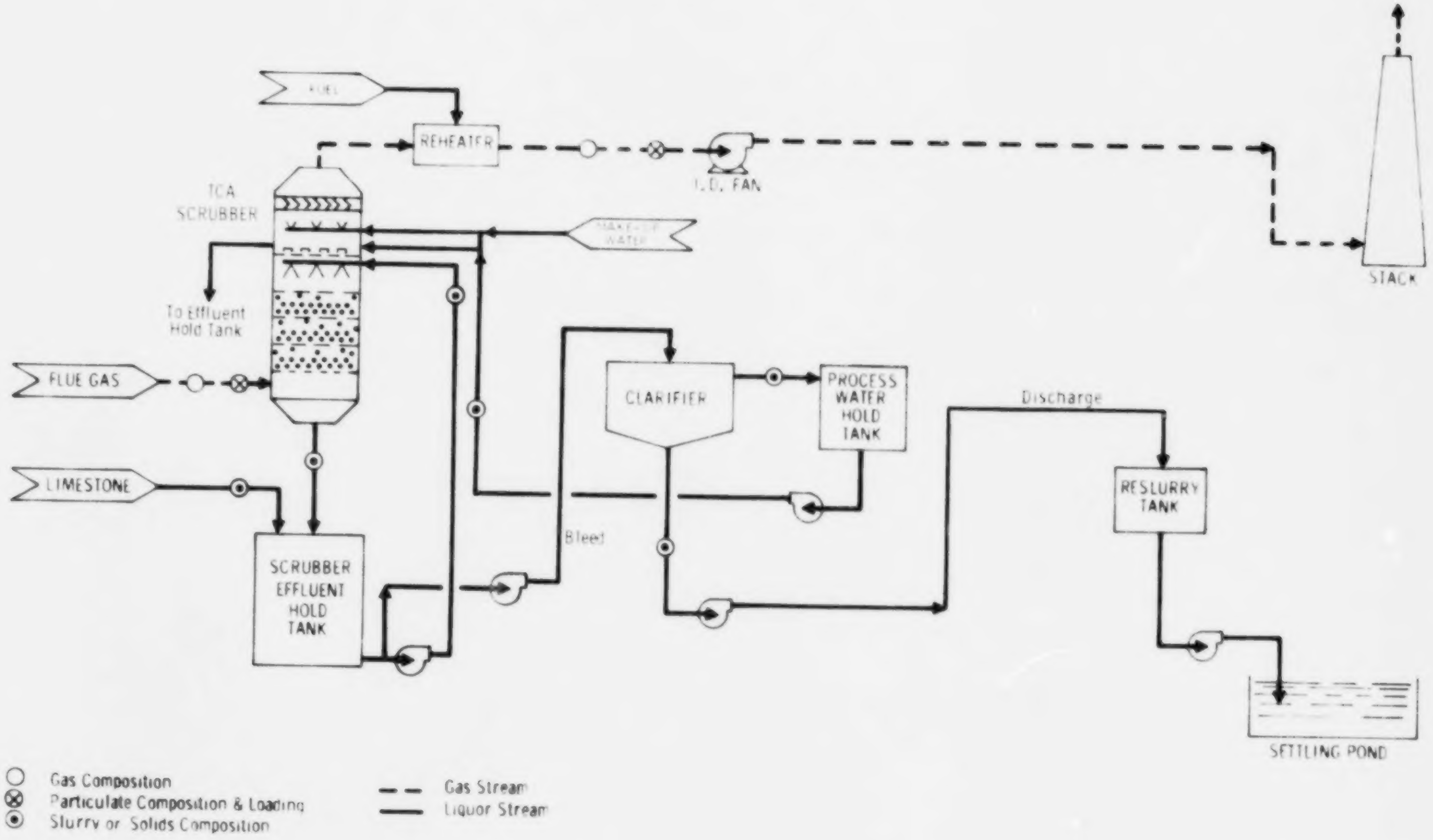

Figure 3-6. Typical Process Flow Diagram for TCA System

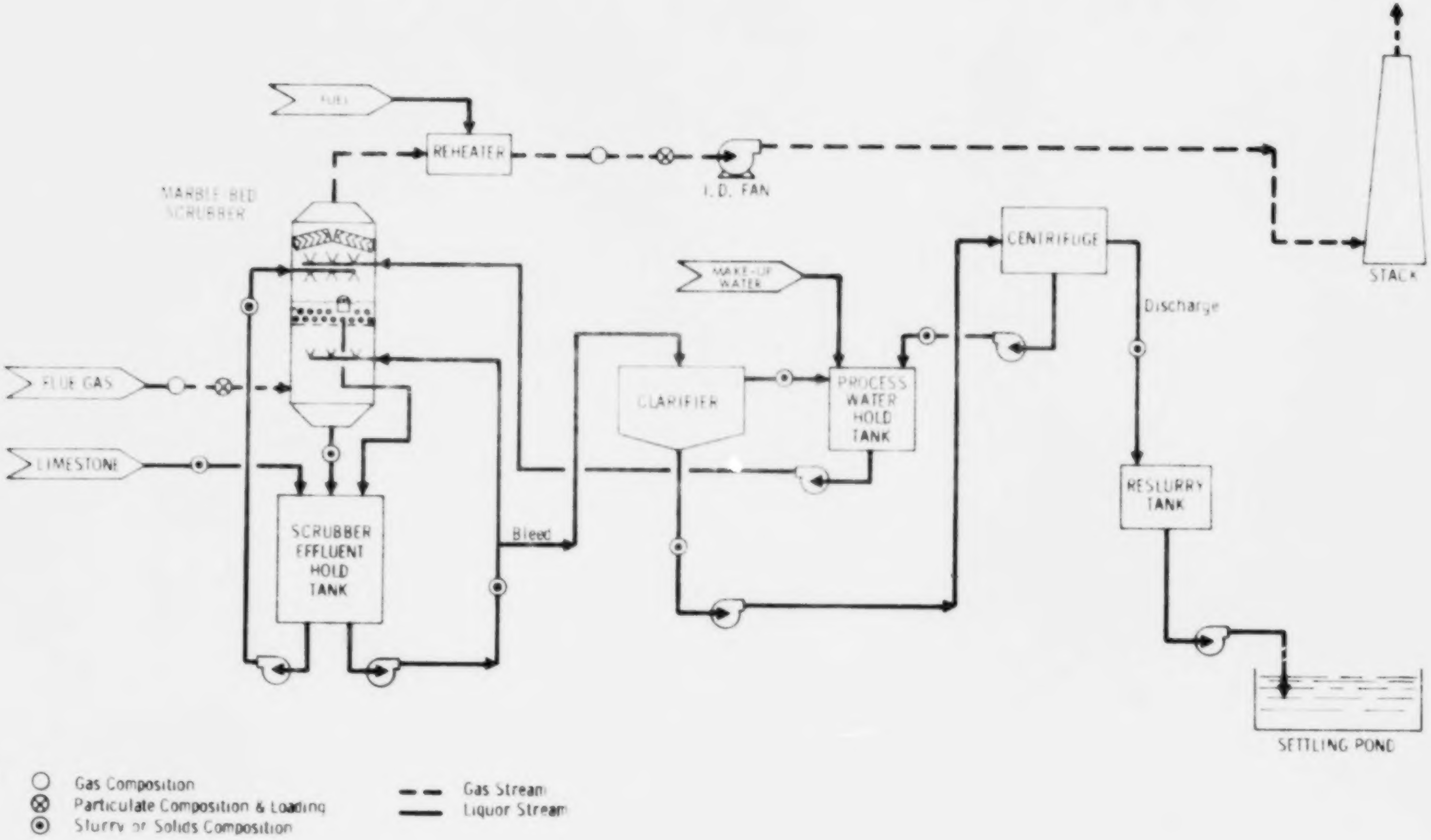

Figure 3-7. Typical Process Flow Diagram for Marble-Bed System

For all systems, gas is withdrawn from the boiler ahead of the power plant particulate removal equipment so that the entrained particulate matter (fly ash) can be introduced into the scrubber. The gas flow rate to each scrubber is measured by venturi flow meters and controlled by dampers on the induced-draft fans. The concentration of sulfur dioxide in the inlet and outlet gas streams is determined continuously by Du Pont photometric analyzers. Inlet and outlet particulate loadings are measured using a modified EPA particulate train.

The scrubbing systems are controlled from a central graphic panelboard. An electronic data acquisition system is used to record the operating data. The system is hard wired for data output in engineering units directly on magnetic tape, and on-site display of selected information is available. Also, important process control variables are continuously recorded, and trend recorders are provided for periodic monitoring of selected data sources.

Figure 3-8 is a view of the scrubber area looking toward the power station. Figure 3-9 is a view of the operations building and thickener area. Figure 3-10 is a view of the scrubber control room.

3.3 EPA PILOT PLANT SUPPORT

Two smaller scrubbing systems (300 acfm each), which are capable of operating over a wide range of conditions, have been installed at the EPA facility in Research Triangle Park, North Carolina, in support of the Shawnee prototype testing activities. The small pilot scale scrubber systems are capable of simulating the TCA scrubber system and have generated large quantities of limestone and lime wet-scrubbing data on certain TCA configurations.

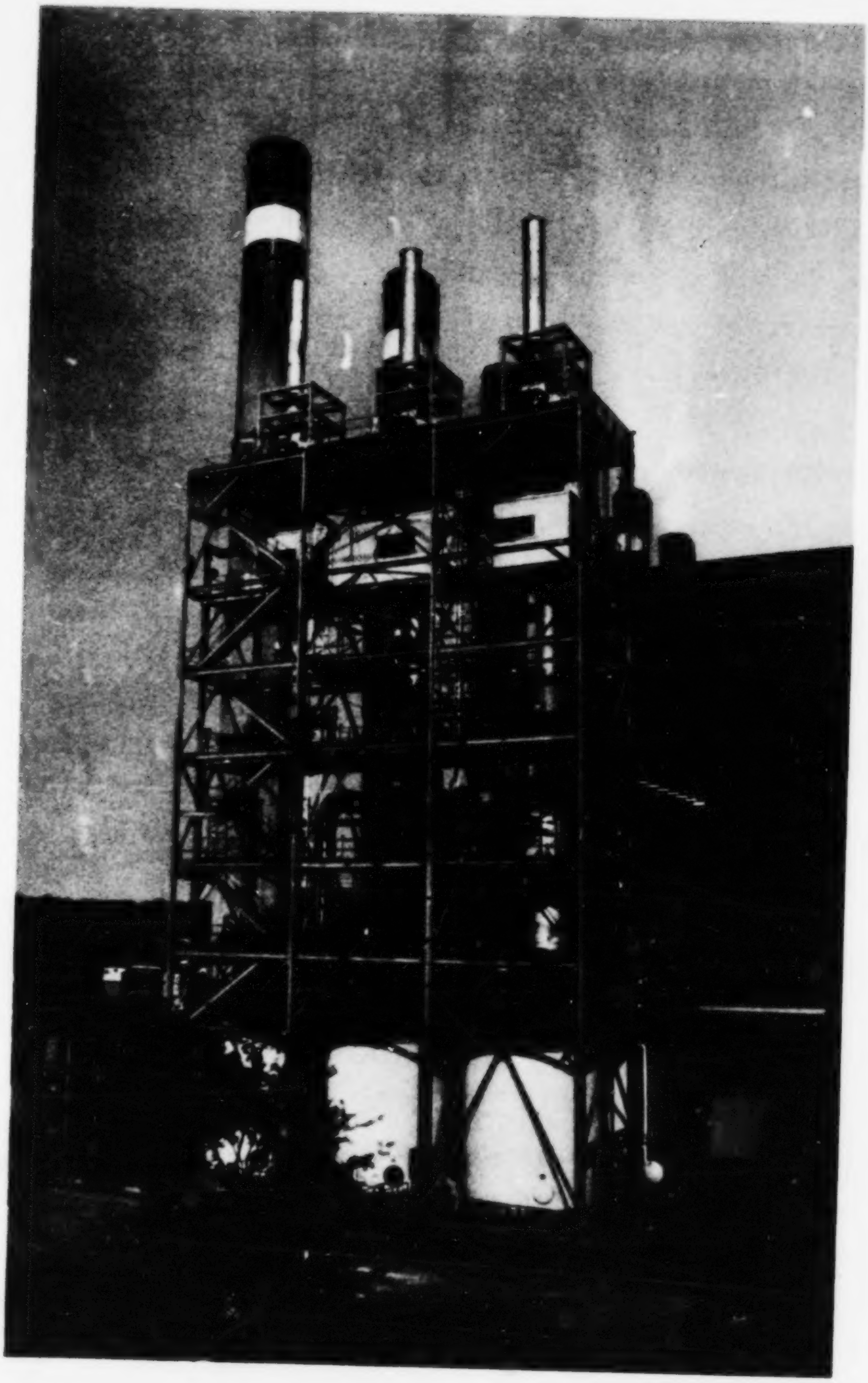

Figure 3-8. Scrubber Area

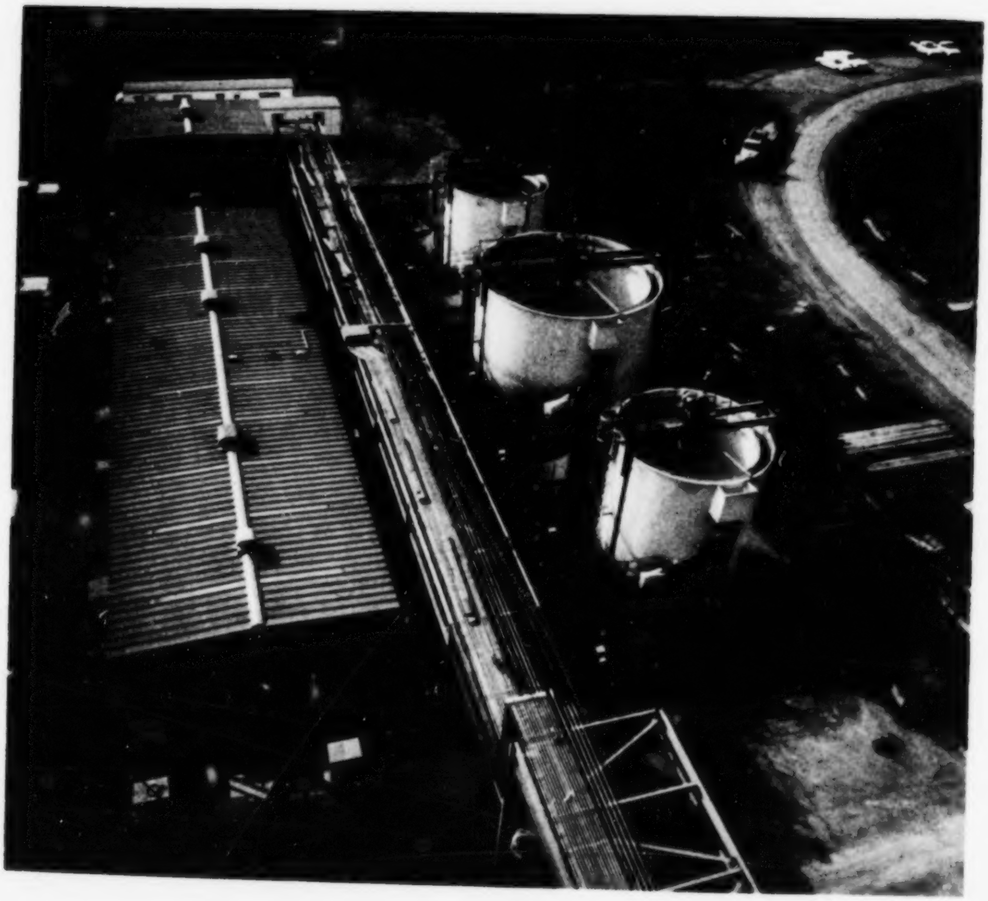

Figure 3-9. Operations Building and Thickener Area

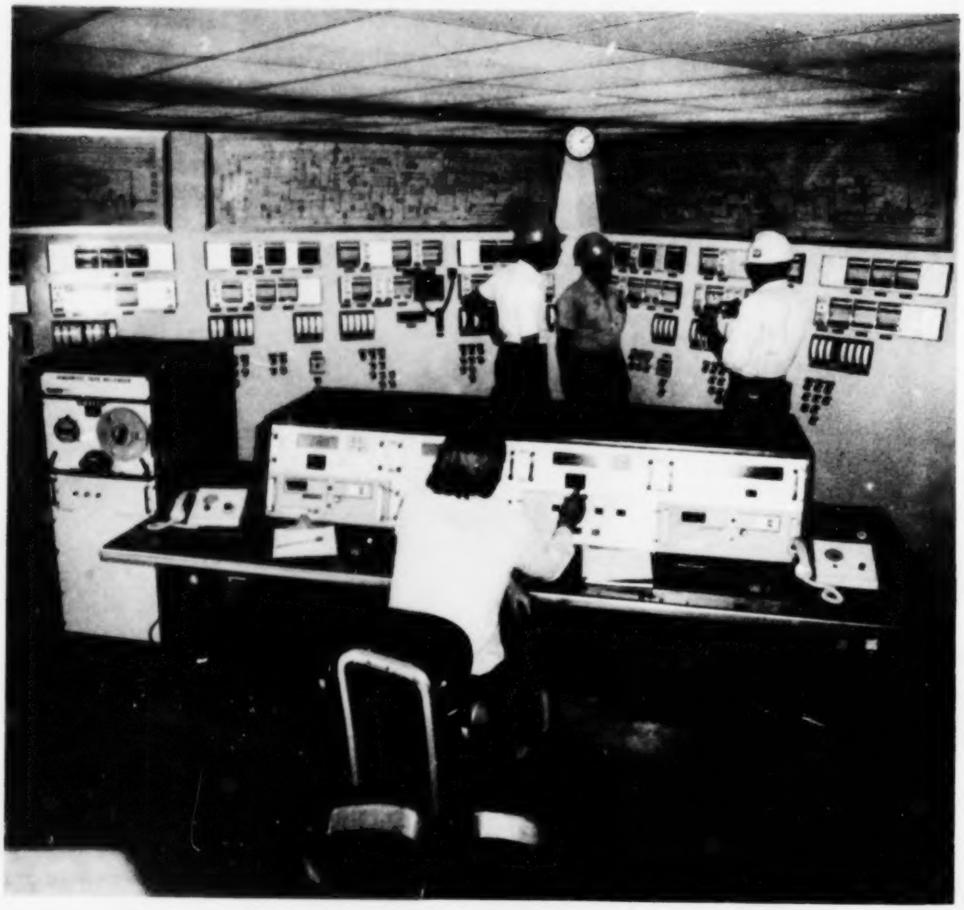

Figure 3-10. Control Room

Section 4

TEST PROGRAM

This section contains a description of the Shawnee test program (the Phase III program) which ran from March 1972 through October 1974. As mentioned previously, an advanced Shawnee test program was begun in October 1974 (see Reference 3).

The test program schedule is presented in Figure 4-1. Test results are presented in Sections 5 through 9 of this report. Operating experience is summarized in Section 10. Results of particulate removal tests, taken at various times during the program, are presented in Section 11. The test data are analyzed in Sections 12 through 14. A listing of the operating periods for the three scrubber systems during reliability testing from March 1973 through October 1974 is presented in Appendix B.

In this report, all gas velocities and liquid-to-gas ratios are at scrubber operating conditions, i.e., saturated gas at scrubber temperature. With flue gas operations, the scrubber temperature is approximately 125°F. The gas velocities are all superficial velocities.

4.1 TEST PERIODS AND TEST PROGRAM SCHEDULE

The following sequential test blocks were defined for the Shawnee test program:

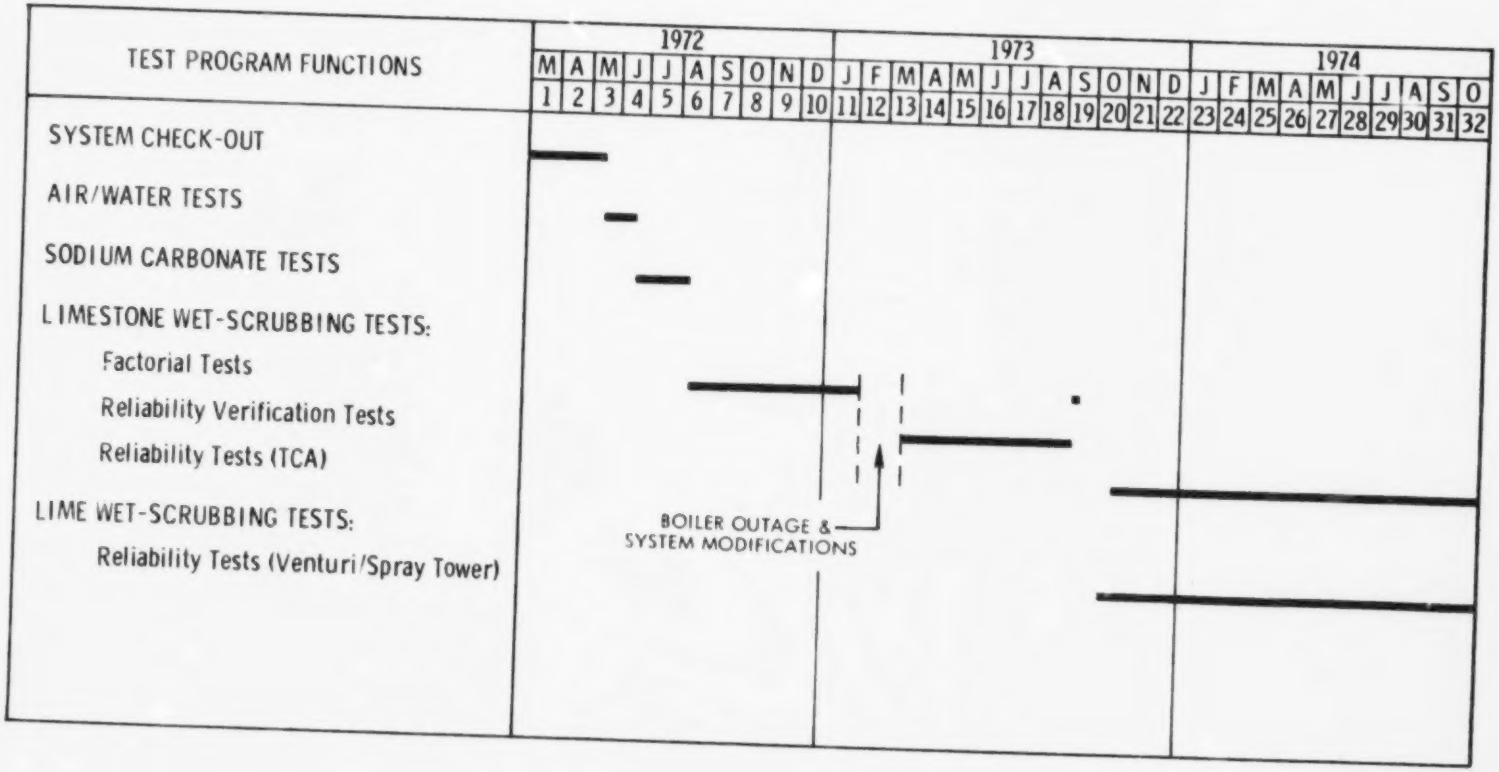

Figure 4-1. Shawnee Test Schedule

(1) Air/water tests

(2) Sodium carbonate tests

(3) Limestone wet-scrubbing tests

(4) Lime wet-scrubbing tests

4.1.1 Air/Water Tests

These experiments, which used air to simulate flue gas and water to simulate alkali slurry, were designed to determine pressure drop model coefficients* and to observe fluid hydrodynamics (e.g., Marble-Bed turbulent layer) for all three scrubbers in clean systems. Pressure drop tests are summarized in Section 5.1, and fitted pressure drop models are presented in Section 12.

4.1.2 Sodium Carbonate Tests

Two series of sodium carbonate tests were designed. The first, or "gas-phase resistance" series, utilized water solutions of sodium carbonate containing 0.5 to 1.0 wt % sodium ion to absorb SO_2 from flue gas and from a synthetic flue gas composed of air and SO_2. These tests were designed to determine uncertain model coefficients for the gas-side mass transfer resistance under conditions where gas-side mass transfer is rate controlling. The second, or "gas/liquid-phase resistance" series, used sodium carbonate solutions containing 0.1 to 0.5 wt % sodium ion to absorb SO_2 from flue gas and synthetic flue gas. For this series, gas-side mass transfer was not rate controlling, and uncertain model coefficients for the liquid-side mass transfer resistance could be calculated using relationships for gas-side coefficients developed from the "gas-phase resistance" tests. These runs also helped ascertain the absorption capability of liquors associated with some variations of the Double-Alkali scrubbing process over a useful range of operating conditions. A summary of the sodium carbonate test results is presented in Section 5. An analysis of the results and equations for predicting SO_2 absorption using the fitted gas and liquid-side resistances are presented in Section 13.

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*Mathematical models describing pressure drop, particulate removal, and sulfur dioxide removal for the three scrubber systems have been presented in Reference 6.

4.1.3 Limestone Wet-Scrubbing Tests

The primary objectives of the limestone wet-scrubbing test sequence were:

(1) To characterize, as completely as practicable, the effect of important independent variables on particulate removal and SO_2 removal.

(2) To identify and resolve operating problems, such as mist eliminator scaling and plugging.

(3) To identify areas or regions for reliable operation of the three scrubber systems, consistent with reasonable SO_2 removal, and to choose economically attractive operating configurations from within these regions.

(4) To determine long-term operating reliability with attractive configurations for one or more of the scrubber systems and to develop definitive process economics data and scale-up factors.

To accomplish the first objective, a large number of short-term (< 1 day/test) limestone factorial tests were made on each scrubber system. The test data for this series are presented in Section 6 and are analyzed in Section 14.

To accomplish the second and third objectives, a relatively small number of longer term (~ 500 hour) limestone reliability verification tests were made on each scrubber system. These longer term tests were also useful in (1) obtaining reliable material balances and (2) quantifying variations in SO_2 and particulate removal and in system slurry compositions with time. The results of the limestone reliability verification tests are given in Section 7.

The fourth objective was accomplished by running long-term limestone reliability tests, lasting up to 3 months in duration, on the TCA system. The results of these tests are given in Section 8.

4.1.4 Lime Wet-Scrubbing Tests

The objectives of the lime wet-scrubbing test sequence were identical to the objectives for the limestone wet-scrubbing sequence just described. As originally planned, the testing was to be divided into the same three categories: (1) short-term factorial tests, (2) longer term reliability verification tests, and (3) long-term reliability tests. Subsequently, it was planned to begin the lime testing with long-term reliability tests on the venturi/spray tower system and to perform the factorial and reliability verification tests at a later date (after October 1974). The results of the long-term lime reliability tests are given in Section 9.

4.2 TEST DESIGNS

The test sequences for the air/water, sodium carbonate, limestone factorial, and limestone reliability verification experiments were all full or partial factorial* designs based upon the chosen independent variables, their levels, and the restraints of time (outlined in Figure 4-1). The choice of the independent variables and their levels was based upon pilot plant test results, the restrains of the system, and results from mathematical models which relate the dependent and independent variables.

For the air/water testing, the primary dependent variable was pressure drop and the controlled independent variables were: gas rate, liquor rate, venturi plug opening, number of grids and spheres in the TCA, and height of marbles in the Marble-Bed.

For the sodium carbonate testing, the dependent variable was SO_2 removal and the controlled independent variables were: gas rate, liquor rate, venturi plug opening, SO_2 inlet gas concentration, height of marbles in the Marble-Bed, scrubber inlet liquor pH, scrubber liquor sodium concentration, and stoichiometry (moles sodium added per mole SO_2 absorbed).

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*A factorial experiment is the name commonly applied to an experiment wherein the effects of several independent variables (factors) on the dependent variables are determined at each of two or more levels.

For the limestone factorial testing, the dependent variable was SO_2 removal and the controlled independent variables were: gas rate, liquor rate, venturi pressure drop, number of headers in spray tower, scrubber inlet liquor pH, and number of grids and spheres in the TCA. Non-controlled independent variables were SO_2 inlet gas concentration and scrubber slurry temperature.

For the limestone reliability verification testing, the dependent variables were scrubber system scaling and plugging potential, and the controlled independent variables were: gas rate, liquor rate, scrubber inlet liquor pH, effluent residence time, solids concentration in the scrubber recirculation slurry, and solids concentration in the discharge sludge. Non-controlled independent variables were SO_2 inlet gas concentration and scrubber slurry temperature.

4.3 ANALYTICAL PROGRAM

Samples of slurry, flue gas, limestone, lime, and coal were taken periodically for chemical analyses, particulate mass loading, and limestone reactivity tests during the wet-scrubbing experiments. Locations of slurry and gas sample points are shown on Figures 3-5, 3-6, and 3-7. A summary of the analytical methods for determining important species in the slurry solids and slurry liquor is presented in Table 4-1. A listing of the compositions of the raw materials used in the testing program is presented in Appendix C.

Table 4-1

FIELD METHODS FOR BATCH CHEMICAL ANALYSIS
OF SLURRY AND ALKALI SAMPLES

SPECIES DESIRED	FIELD METHOD	
	SOLIDS	LIQUIDS
Sodium	-	Atomic Absorption
Potassium	-	Atomic Absorption
Calcium	X-ray Fluorescence	Atomic Absorption
Magnesium	X-ray Fluorescence	Atomic Absorption
Sulfite	Amperometric Titration	Amperometric Titration
Total Sulfur	X-ray Fluorescence	$Ba(ClO_4)_2$ Titration
Carbonate	Evolution	Infrared Analyzer
Chlorides	-	Potentiometric Titration

Six Du Pont photometric analyzers were utilized for continuous SO_2 gas analyzing at the inlets and outlets of all three scrubbers. Values of pH were monitored on a continuous basis using fifteen Universal Interlox pH analyzers. Three Universal Interlox electrolytic analyzers were used to monitor electrical conductivity. A modified EPA particulate train (manufactured by Aerotherm/Acurex Corporation) was used to measure mass loading at the scrubber inlets and outlets.

4.4 DATA ACQUISITION AND PROCESSING

Operating and analytical data were recorded automatically onto magnetic tapes at the test facility. These were sent to the Bechtel Corporation offices in San Francisco for processing. Additional data was recorded manually in operating logs and graphs by on-site personnel.

4.4.1 Operating Data (Scan Data Acquisition)

Over 150 pieces of "scan data" (flow rate, temperature, pH, etc.) were recorded automatically at fixed time intervals onto magnetic tape at the test facility. The scan data acquisition system was designed and installed by Electronic Modules Corporation, and the tape recorder was supplied by Cipher Data Products Corporation. A backup printed record on paper tape was available if the recorder malfunctioned.

The scan data tapes were mailed to Bechtel Corporation in San Francisco for processing. Preliminary processing consisted of reading the tapes, translating the coded data into comprehensible numbers, and preparing a report of the data.

4.4.2 Analytical Data

The analytical data acquisition system, which recorded the results of laboratory analyses on magnetic tape, was designed and (in part) installed by Radian Corporation. A mini-computer received inputs, either directly from laboratory instrumentation or indirectly by reading cards. The mini-computer performed certain calculations and entered the resultant data on magnetic tape. The system generated, on-site, a printed summary sheet of analytical data for each sample.

In San Francisco, data on tapes received from the test facility was entered into a data base. The data were sorted, further calculations were made (e.g., percent sulfite oxidation, stoichiometric ratio), and reports were prepared which present the data covering a specified period for a given scrubber.

4.5 MATERIALS EVALUATION PROGRAM

TVA has conducted a study for the evaluation of corrosion and wear of plant equipment and test specimens (coupons) at the Shawnee facility. A summary of this study is presented in Section 10.11 of this report. TVA reports on materials evaluation are included in Appendices J and K.

Section 5

AIR/WATER AND SODIUM CARBONATE TEST RESULTS

The results of initial testing with air and water and with sodium carbonate (soda ash) solution are presented graphically in this section and tabulated in Appendix D. Pressure drop data are presented in Section 5.1. SO_2 removal data from sodium carbonate tests are presented in Section 5.2.

5.1 PRESSURE DROP DATA FROM AIR/WATER AND SODIUM CARBONATE TESTS

The pressure drop data for the air/water and sodium carbonate runs for the three scrubber systems are shown in Figures 5-1 through 5-6 and in Tables D-1 through D-9 of Appendix D. Tests with both air and flue gas were made in each of the scrubbers. An analysis of these data, including equations fitted to the primary variables, is presented in Section 12.

5.1.1 Venturi Scrubber

The effects of throat gas velocity (40 to 100 ft/sec), liquid-to-gas ratio (15 to 50 gal/mcf), and plug opening (25 to 80 percent) on venturi pressure drop* are shown in Figures 5-1 and 5-2. The pressure drop is a strong function of all three variables.

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*Measured from venturi inlet duct to spray tower inlet duct.

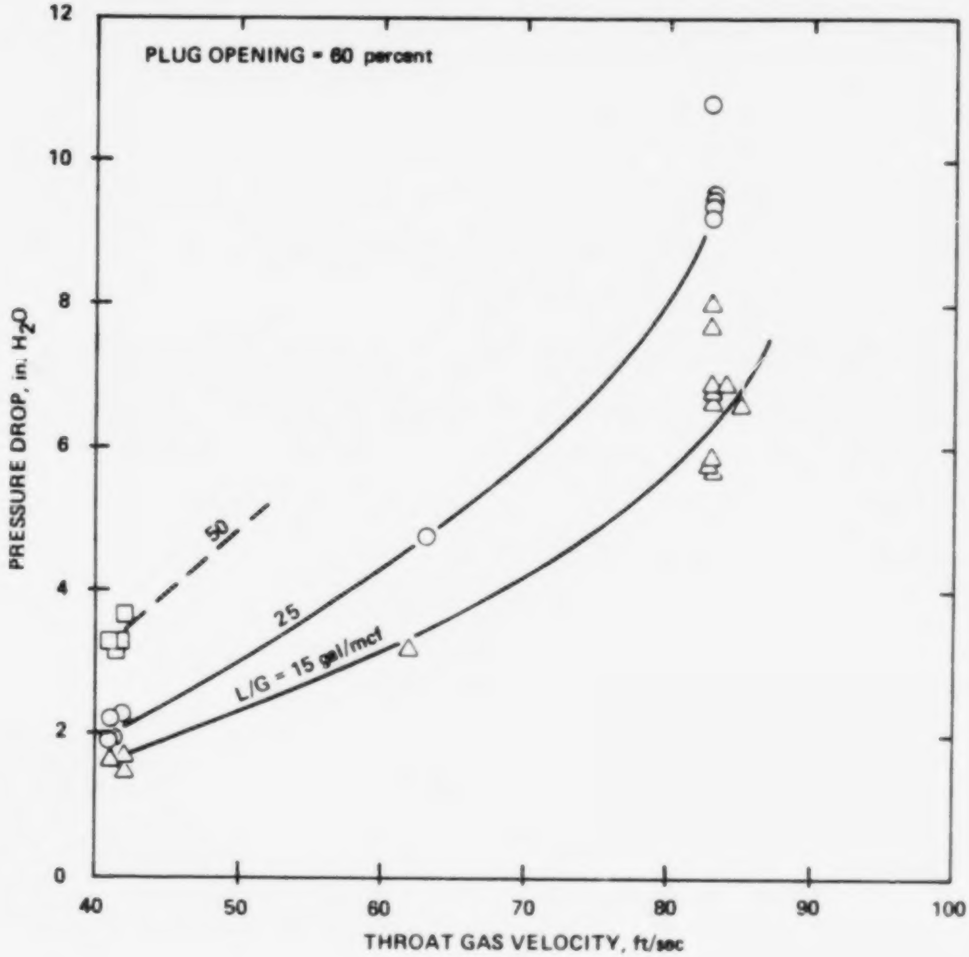

Figure 5-1. Effect of Liquid-to-Gas Ratio and Throat Gas Velocity on Pressure Drop for the Chemico Venturi

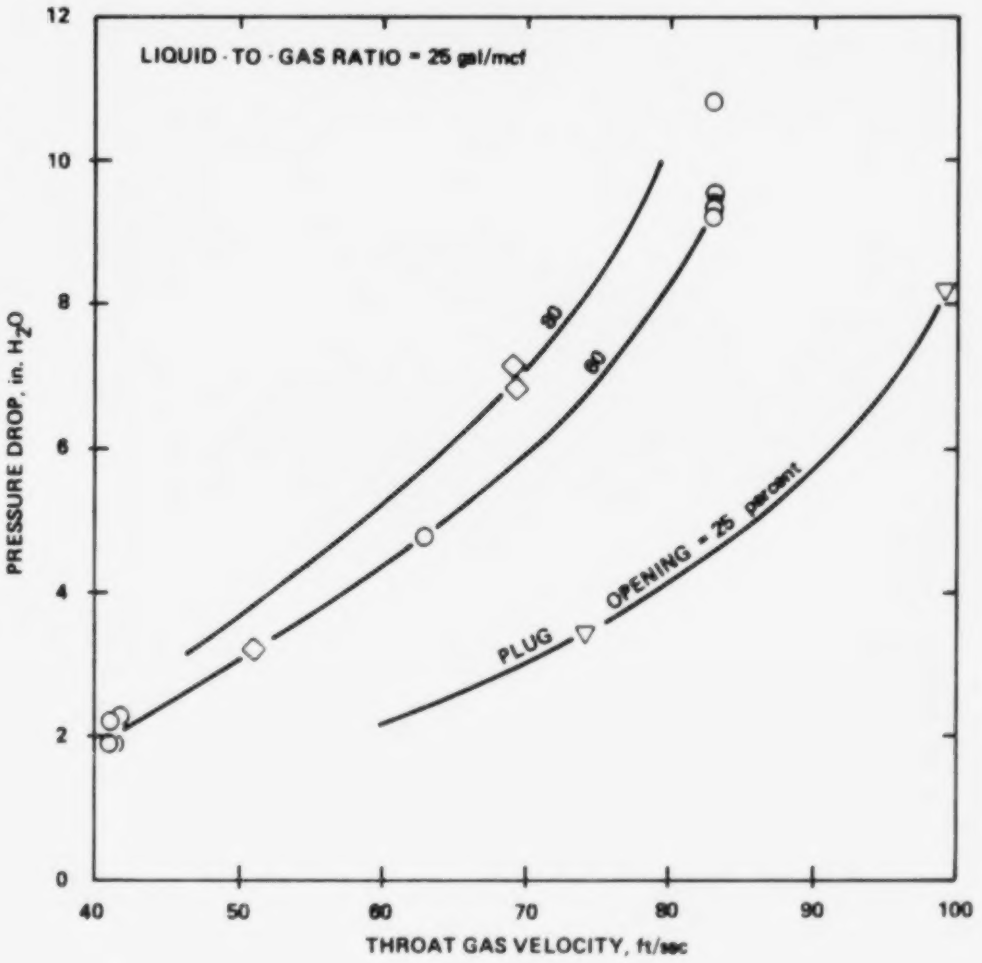

Figure 5-2. Effect of Plug Opening and Throat Gas Velocity on Pressure Drop for the Chemico Venturi

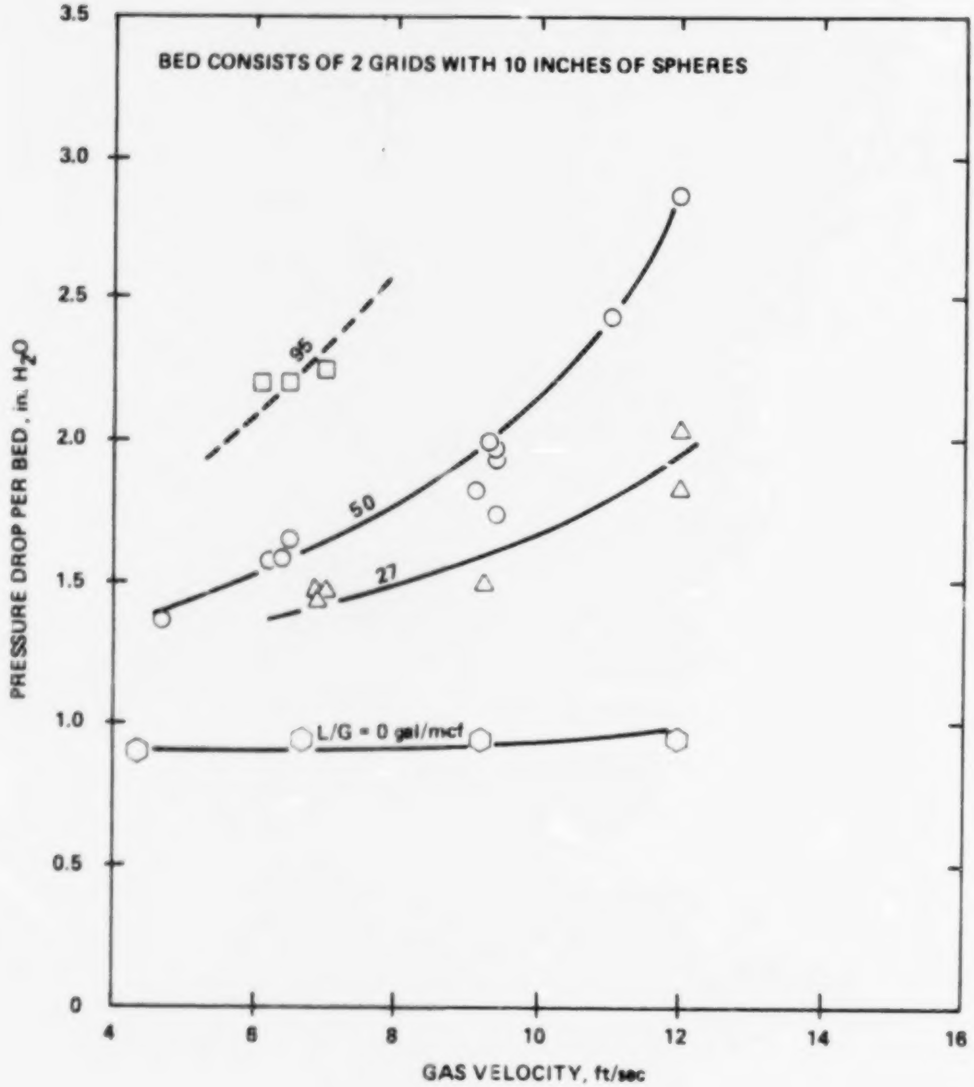

Figure 5-3. Effect of Liquid-to-Gas Ratio and Gas Velocity on Pressure Drop per Bed for the TCA

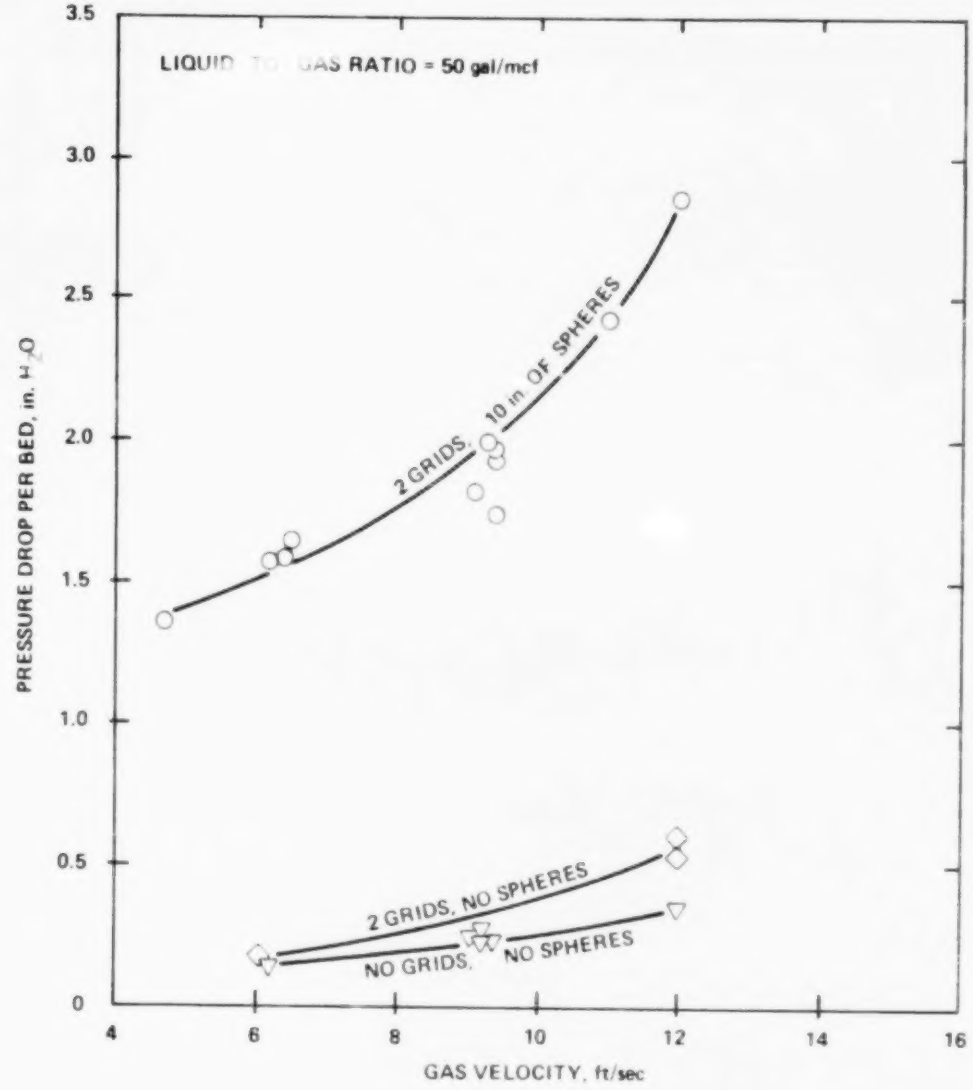

Figure 5-4. Effect of Internals and Gas Velocity on Pressure Drop per Bed for the TCA

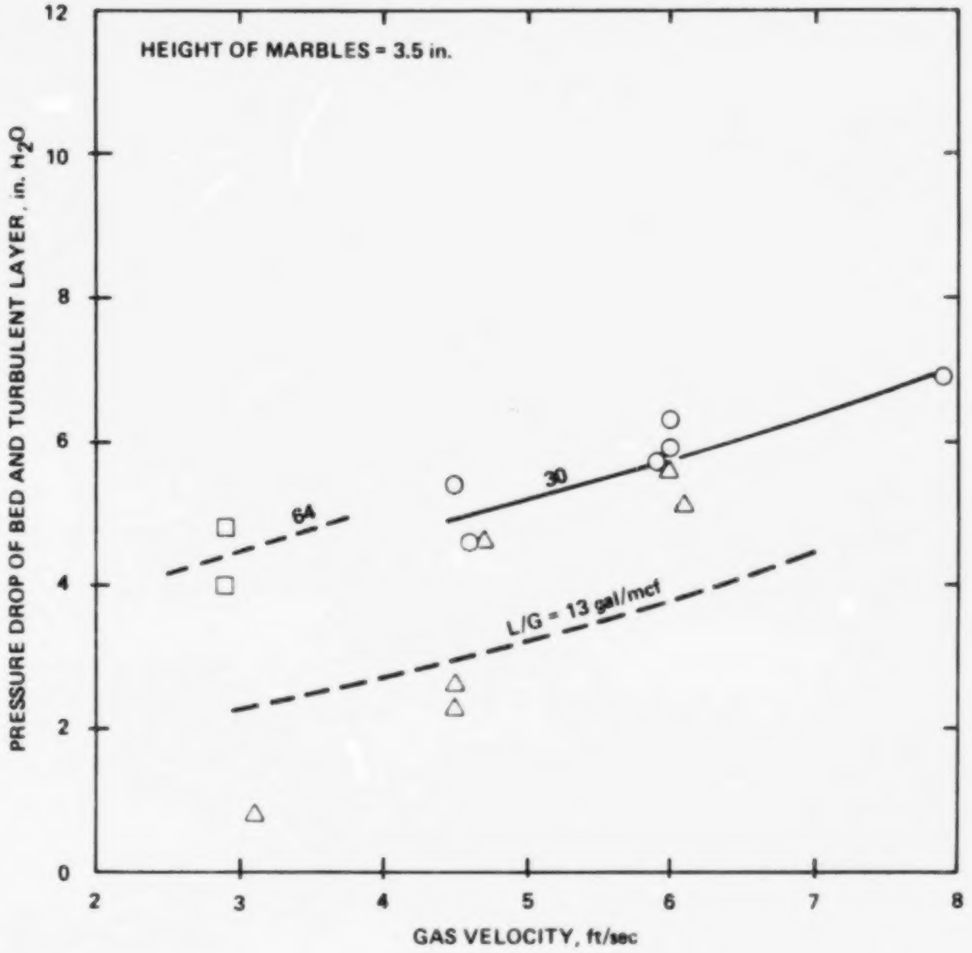

Figure 5-5. Effect of Liquid-to-Gas Ratio and Gas Velocity on Pressure Drop across the Marble-Bed

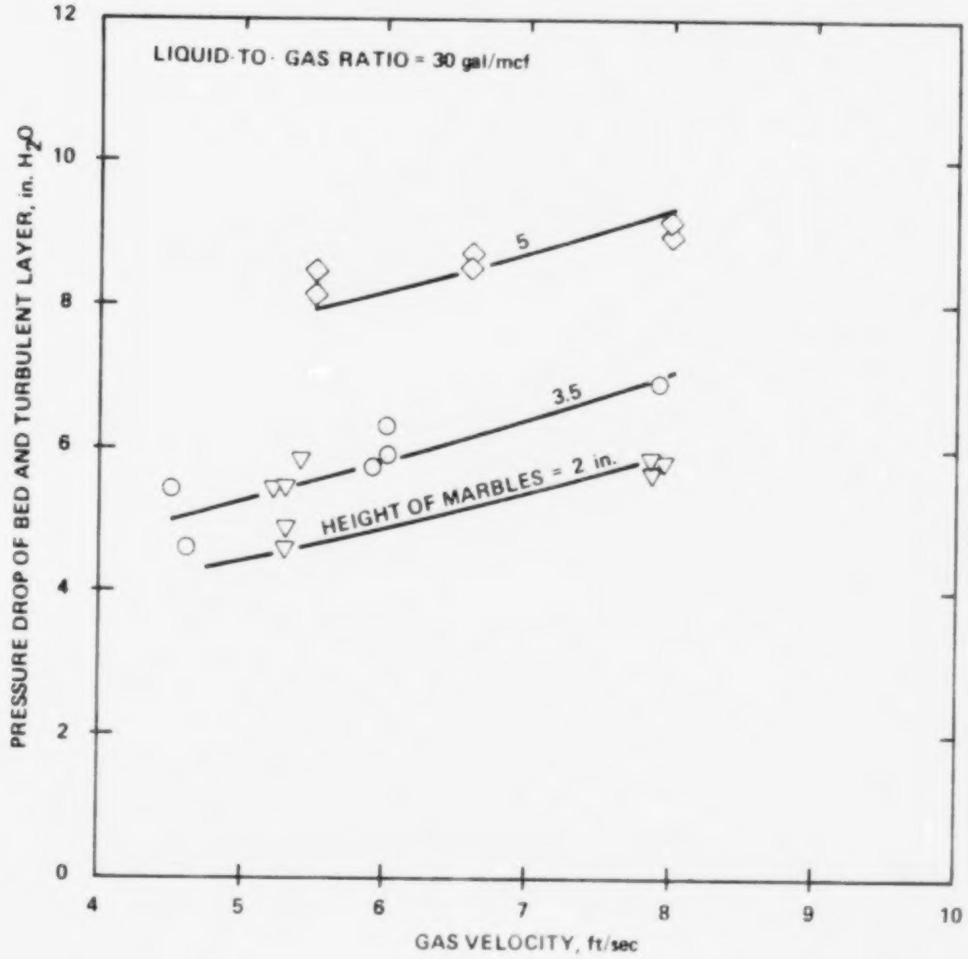

Figure 5-6. Effect of Bed Height and Gas Velocity on Pressure Drop across the Marble-Bed

Plug opening affects both the throat area and the throat length. In Figure 5-2 the increase in pressure drop with plug opening at constant gas velocity is primarily the result of increase in throat length. The relationships giving throat length and throat area as functions of plug opening for the Chemico venturi are presented in Equations 12-2 and 12-3, respectively.

5.1.2 TCA Scrubber - Single Bed

The effects of superficial gas velocity (4 to 12 ft/sec), liquid-to-gas ratio (0 to 95 gal/mcf), and scrubber internals (grids and spheres) on pressure drop across a single TCA bed are presented in Figures 5-3 and 5-4.

In Figures 5-3 and 5-4, pressure drop is shown to be a strong function of gas velocity, liquor rate, and scrubber internals. A single bed consisted of 10 inches static height of 1 1/2 inch, 5 gram spheres plus two wire mesh restraining grids. As seen in Figure 5-4, the empty scrubber and wire mesh grids account for about 10 to 20 percent of the pressure drop across the bed. Because of erosion problems with the wire mesh grids (see Section 10.3.1), they were replaced with bar-grids prior to limestone reliability testing. The bar-grids have a lower pressure drop than the wire mesh grids.

Strictly speaking, single bed pressure drops are not additive for multi-bed columns since there are not two grids for each bed (i.e., three beds consist of four grids and spheres), and entrance and exit effects are not accounted for. Total pressure drops across the TCA scrubber for several internal configurations are tabulated in Tables D-4 through D-6 of Appendix D. Total pressure drop was measured from the entrance of the scrubber presaturation sprays to the scrubber exit downstream from the mist eliminator and its associated wash headers.

5.1.3 Marble-Bed Scrubber

The effects of superficial gas velocity (3 to 8 ft/sec), liquid-to-gas ratio (13 to 64 gal/mcf), and height of marbles (2 to 5 in.) on pressure drop across the marble-bed and the turbulent layer immediately above the bed are shown in Figures 5-5 and 5-6. Pressure drop increases with all three of these variables.

5.2 SULFUR DIOXIDE REMOVAL DATA FROM SODIUM CARBONATE TESTS

A summary of the SO_2 removal data from the sodium carbonate runs is shown in Figures 5-7 through 5-11 and in Tables D-10 through D-16 of Appendix D. The SO_2 removals have all been corrected for the dilution effect of water vapor and reheater gas pickup by the flue gas. Runs were made both with air containing injected SO_2 and with flue gas from Shawnee boiler No. 10.

Sodium carbonate tests were made at conditions in which gas-side mass transfer resistance was controlling (gas side resistance tests) and at

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These tests were designed, primarily, to determine uncertain coefficients in correlation models where gas-side mass transfer resistance is rate controlling.

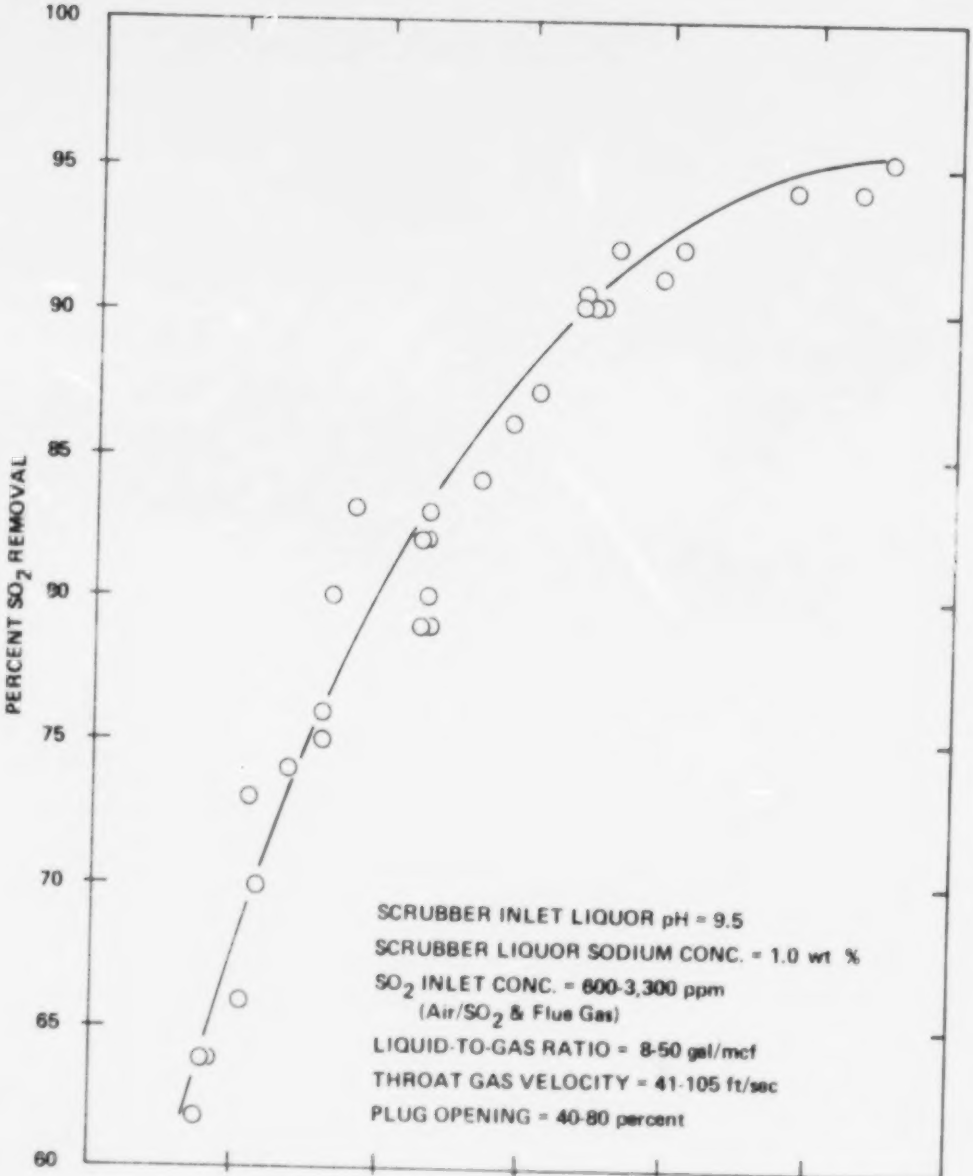

Figure 5-7. Effect of Pressure Drop on SO_2 Removal in the Chemico Venturi (Gas-Side Resistance Tests)

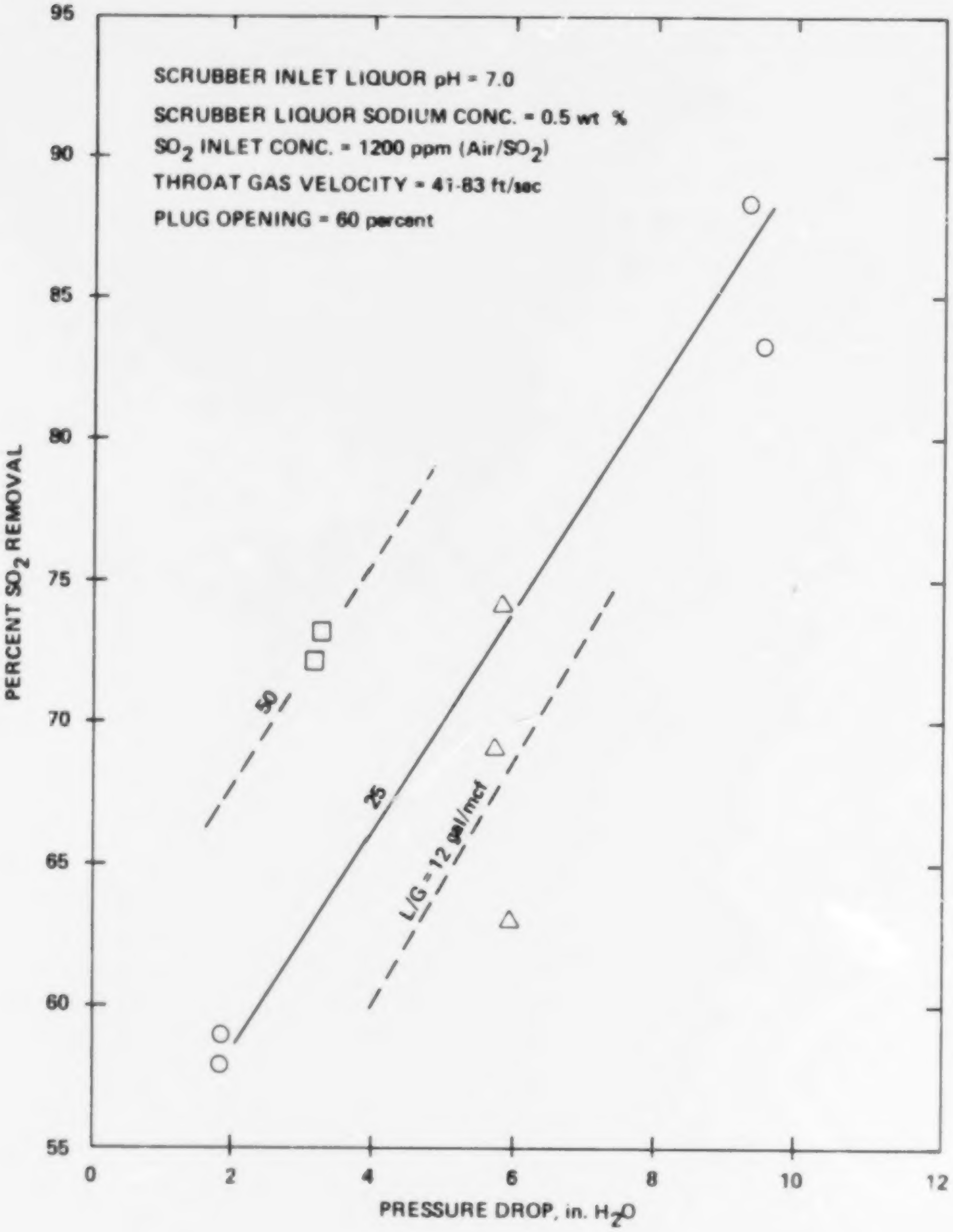

Figure 5-8. Effect of Liquid-to-Gas Ratio and Pressure Drop on SO_2 Removal in the Chemico Venturi (Gas/Liquid-Side Resistance Tests)

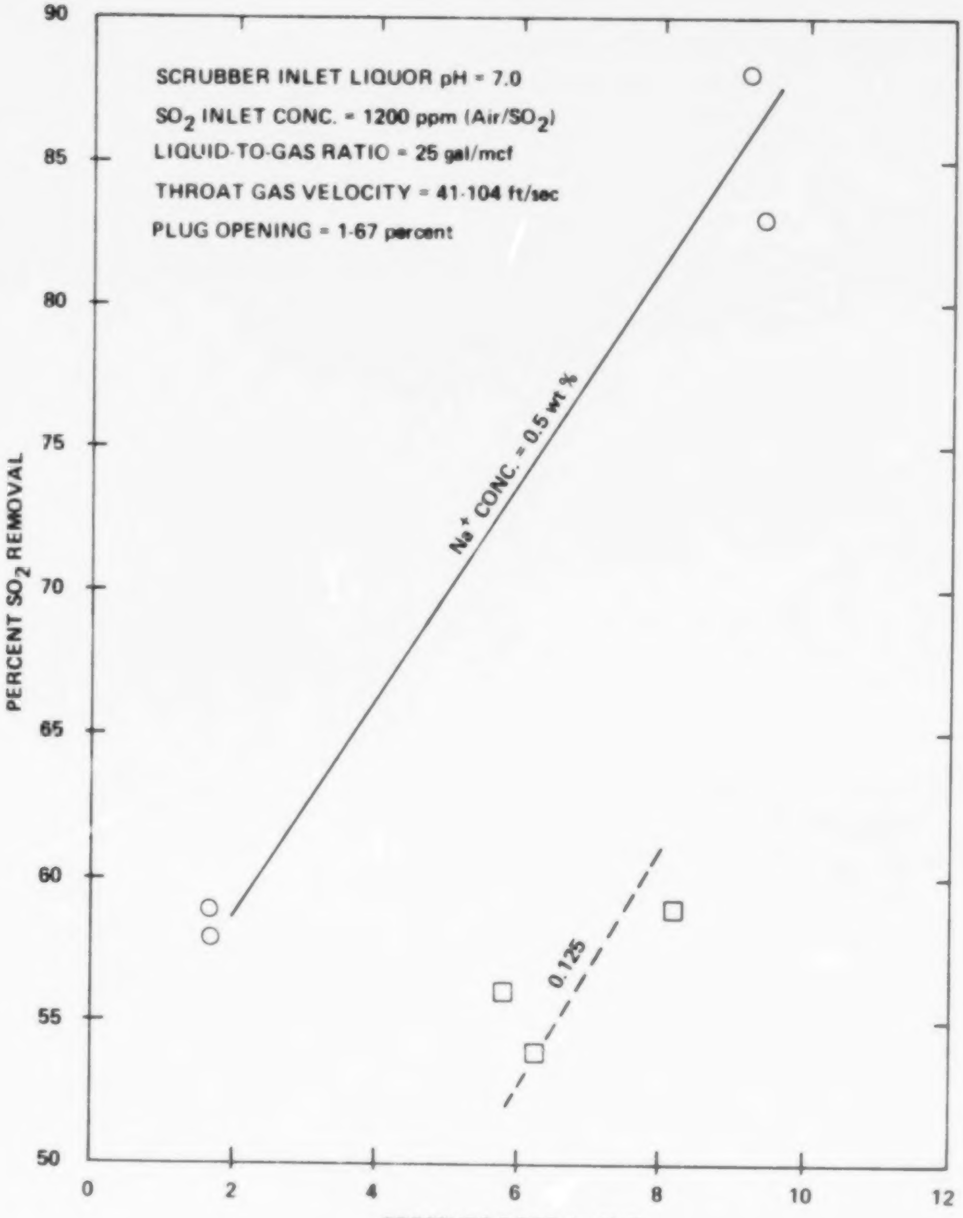

Figure 5-9. Effect of Sodium Concentration and Pressure Drop on SO_2 Removal in the Chemico Venturi (Gas/Liquid-Side Resistance Tests)

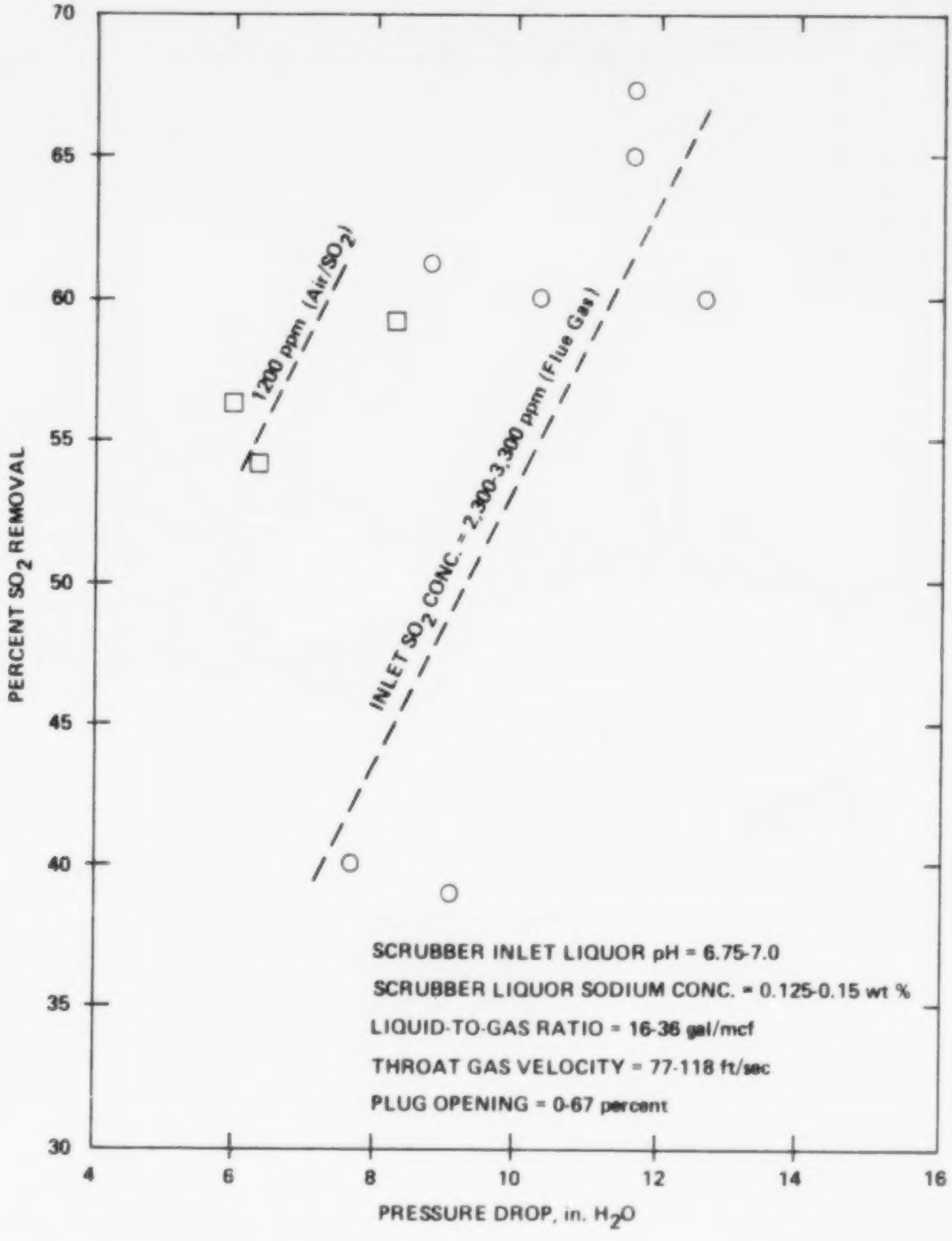

Figure 5-10. Effect of Inlet SO_2 Concentration and Pressure Drop on SO_2 Removal in the Chemico Venturi (Gas/Liquid-Side Resistance Tests)

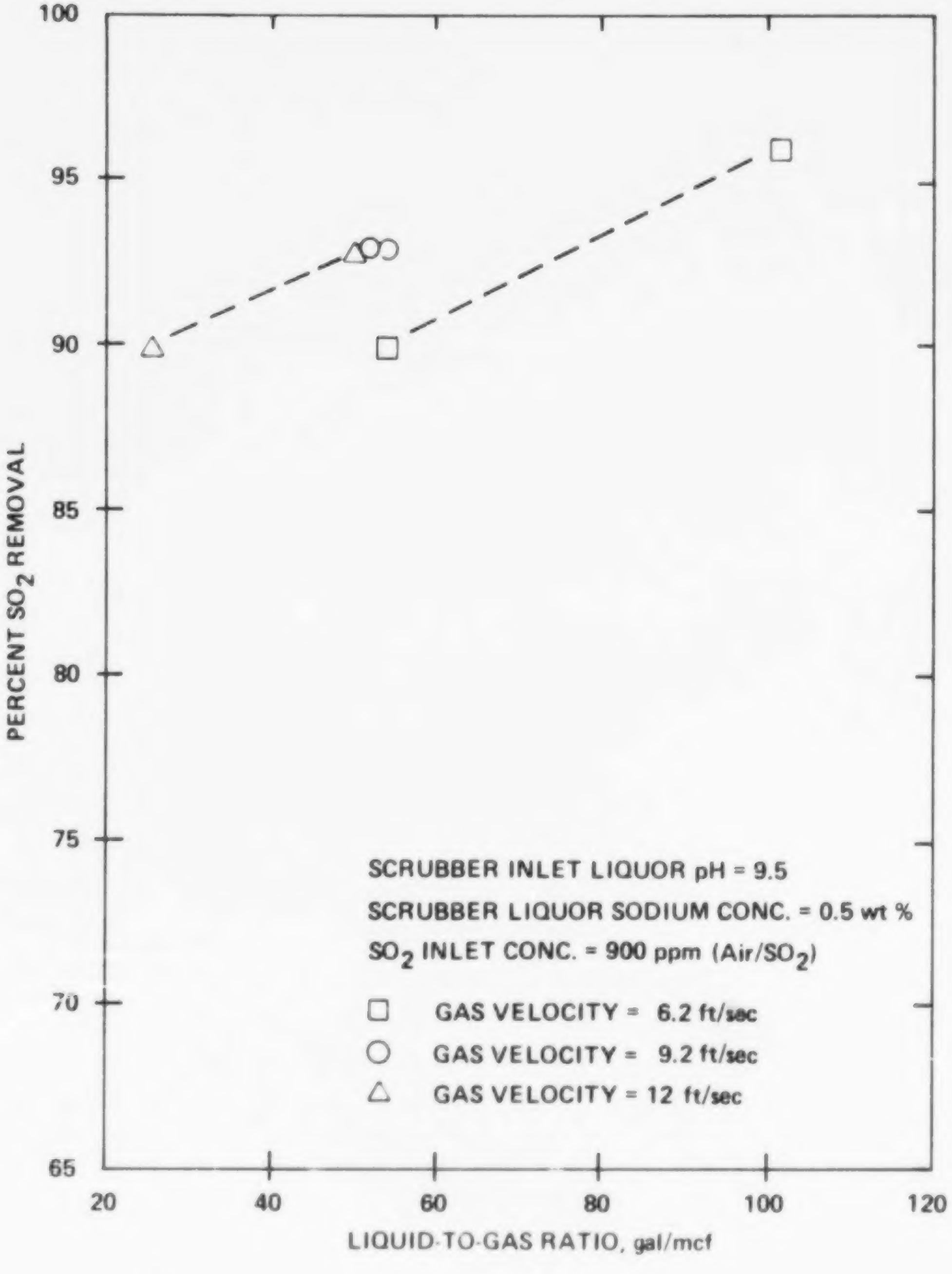

Figure 5-11. Effect of Gas Velocity and Liquid-to-Gas Ratio on SO_2 Removal for the TCA Operated as a Spray Tower (Gas-Side Resistance Tests)

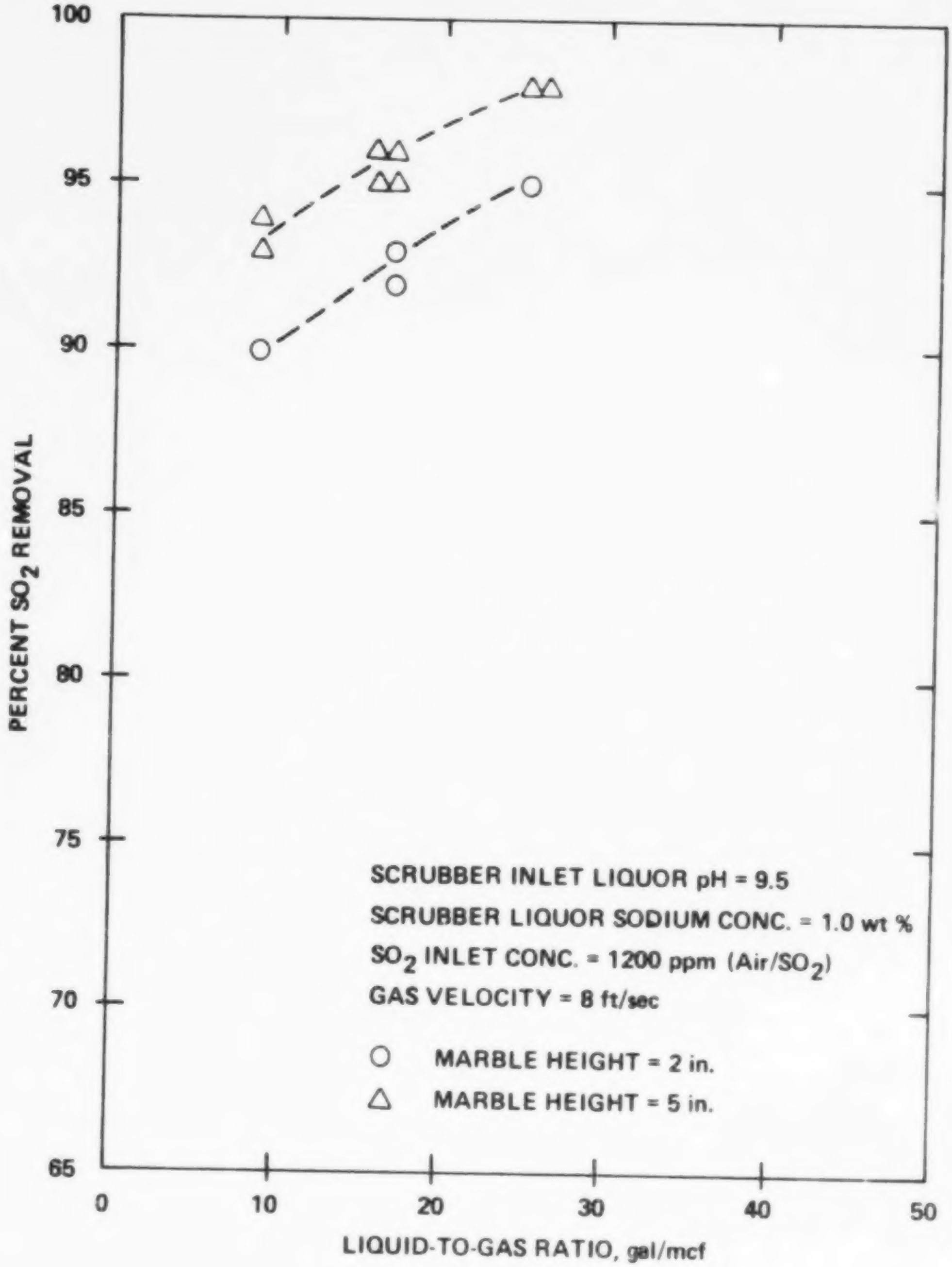

Figure 5-12. Effect of Bed Height and Liquid-to-Gas Ratio on SO_2 Removal in the Marble-Bed Scrubber (Gas-Side Resistance Tests)

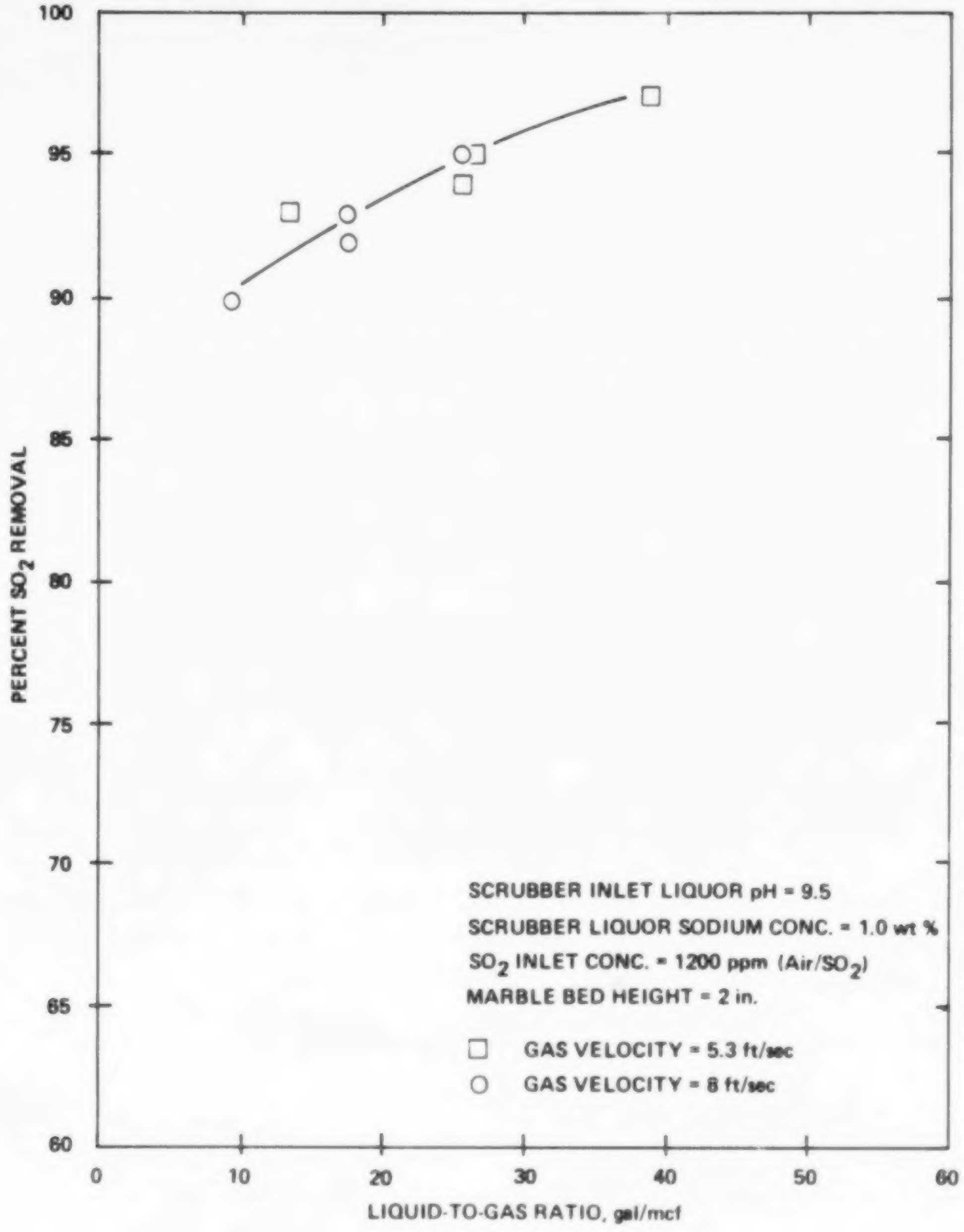

Figure 5-13. Effect of Gas Velocity and Liquid-to-Gas Ratio on SO_2 Removal in the Marble-Bed Scrubber (Gas-Side Resistance Tests)

conditions in which both gas-side and liquid-side mass transfer resistance were important (gas/liquid-side resistance tests). Data from the sodium carbonate tests indicated that gas-side resistance is rate controlling at an inlet pH of 9.5 and Na^+ concentration of 0.5 wt % or higher, and at an inlet pH above 8.5 and Na^+ concentration of 1.0 wt %.

Below these limits of pH and Na^+ concentration, both gas-side and liquid-side mass transfer were controlling. (See Runs 202-1A through 202-1D in Appendix D, Table D-10.)

The gas-side resistance tests came to steady-state within a few minutes after the gas or liquor flow rates, plug positions (or pressure drops), and inlet SO_2 concentrations were changed. The gas/liquid-side resistance tests had to be run over longer periods of time (greater than six hours) because of the apparent large variations in SO_2 removal, due to variations in inlet liquor pH, Na^+ concentration, and stoichiometry.

An analysis of the data from the soda-ash tests for the three scrubber systems is presented in Section 13 of this report. For the gas-side resistance tests, the analysis includes equations representing SO_2 removal for all three scrubbers as a function of the independent variables. The gas/liquid-side resistance tests have been analyzed rigorously only for the venturi scrubber.

5.2.1 Venturi Scrubber

Percent SO_2 removal versus venturi pressure drop for different liquid-to-gas ratios (12 to 50 gal/mcf), liquor sodium concentrations (0.125

to 0.5 wt %) and inlet SO_2 concentrations (1200 to 3300 ppm) are shown in Figures 5-7 through 5-10. Figures 5-1 and 5-2 show venturi pressure drop as a function of throat gas velocity (40 to 100 ft/sec), liquid-to-gas ratio (15 to 50 gal/mcf), and plug position (25 to 80 percent open).

The percent SO_2 removal for the gas-side resistance tests is shown in Figure 5-7. The SO_2 removal increases with pressure drop and is independent of inlet gas SO_2 concentration, which indicates gas-side control of SO_2 transfer.

Low sodium concentration (0.125 to 0.5 wt %) and low inlet liquor pH (6.75 to 7.0) data are shown in Figures 5-8 through 5-10. Here SO_2 removal is shown to be a function of venturi pressure drop, liquor rate, gas rate, sodium concentration, and inlet gas SO_2 concentration. These data indicate that both gas-side and liquid-side mass transfer resistance is important.

5.2.2 TCA Scrubber as a Spray Tower

The effects of liquid-to-gas ratio (25 to 100 gal/mcf) and gas velocity (6.2 to 12 ft/sec) on SO_2 removal for the gas-side resistance tests are shown in Figure 5-11. The data are for the TCA with no internals (TCA operated as a spray tower).[*] The SO_2 removal at higher values of removal (90 to 100 percent) depends on both liquor rate and gas velocity.

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[*] Gas-side resistance tests with the TCA in its normal three-bed configuration resulted in SO_2 removals greater than 99 percent.

5.2.3 Marble-Bed Scrubber

The effects of liquid-to-gas ratio (8 to 27 gal/mcf), marble height (2 and 5 inches), and gas velocity (5.3 and 8 ft/sec) on SO_2 removal for the gas-side resistance tests are shown in Figures 5-12 and 5-13. The SO_2 removal at higher values of removal (90 to 100 percent) depends on liquor rate and marble height, but is independent of gas velocity at constant L/G.

Section 6

LIMESTONE FACTORIAL TEST RESULTS

The significant SO_2 removal data from the limestone short-term ($<$ 1 day per test) factorial testing on the three scrubber systems are presented graphically in this section. A complete chronological tabular listing of the factorial data is presented in Appendix E. Properties of coal and limestone used during the tests can be found in Appendix C.

The factorial tests were designed to determine the effects of the primary independent variables (e.g., gas and liquor flow rates) on SO_2 removal for the scrubber systems. An analysis of the data is presented in Section 14 of this report where closed-form equations, compatible with boundary restraints, are presented for predicting SO_2 removal. Variables which were found to be significant by a statistical analysis of the data were introduced into the closed-form equations.

The initial block of limestone factorial testing on the three scrubber systems was made from August 1972 through January 1973 (Tables E-1 through E-3, Appendix E). During this period, it was not possible to operate the test facility in a totally closed liquor loop without facility modifications.* In closed liquor loop operation, the raw water input to the system is equal to the water normally exiting the system in the humidified flue gas and in the settled sludge. Settled sludge concentrations in lime/limestone wet-scrubbing systems are normally equal to or greater than 38 percent by weight of solids. During the factorial testing, water input was excessive, and sludge with less than 38 wt % solids had to be discharged from the systems.

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* The modifications were completed during a five-week boiler outage in February and March 1973 (see Figure 4-1). These modifications are discussed in Section 10.1.

A second block of limestone factorial testing was made with the spray tower in September 1973, under closed liquor loop operation (Table E-4, Appendix E). The spray tower system had been modified during the February 1973 boiler outage to increase the maximum slurry flow to the spray headers from 600 to 1200 gpm. For the spray tower, only the closed liquor loop factorial data will be discussed in this report. The earlier open liquor loop data (Table E-1, Appendix E) have been discussed in Reference 2.

A comparison between the open liquor loop factorial data for the scrubber systems and longer term closed liquor loop replicate runs has shown that SO_2 removal is not significantly affected by liquor composition within the region investigated. Also, models developed for predicting SO_2 removal have shown that, at a specified scrubber inlet liquor pH, the SO_2 removal efficiency is not significantly affected by liquor composition within the region investigated (see Section 14). It is presumed, therefore, that the factorial data generated during open liquor loop operation is applicable for systems operating with closed liquor loops.

Although satisfactory material balance closures could not be obtained during the limestone factorial testing, confidence in the generated data is based on the following:

- Wet chemical analyses for SO_2 in the inlet and exit gas streams repeatedly corroborated Du Pont SO_2 analyzer measurements.
- Sulfur removals in longer term closed liquor loop limestone runs, with excellent material balance closures for sulfur (see Sections 7 and 8), were in close agreement with factorial replicate runs for the scrubber systems.

6.1 SO_2 REMOVAL RESULTS

For the data presented graphically in this section, replicate runs have been drawn as single data points, with the average value and range of values for SO_2 removal indicated. All of the replicate runs are listed in Appendix E.

6.1.1 Venturi Scrubber (Table E-1, Appendix E)

The effect of gas and liquor flow rate on SO_2 removal for the venturi scrubber with 9 inches of pressure drop is shown in Figure 6-1. The data indicate that SO_2 removal is a function of liquor rate but is only slightly affected, if at all, by gas rate within the region investigated. SO_2 removal was not significantly affected by pressure drop within the region investigated (6 to 12 inches H_2O).

6.1.2 Spray Tower (Table E-4, Appendix E)

The effect of gas and liquor flow rate and inlet liquor pH on SO_2 removal for the four-header spray tower is shown in Figure 6-2. The data indicate that SO_2 removal is a significant function of liquor rate, gas rate (gas velocity), and inlet liquor pH within the region investigated.

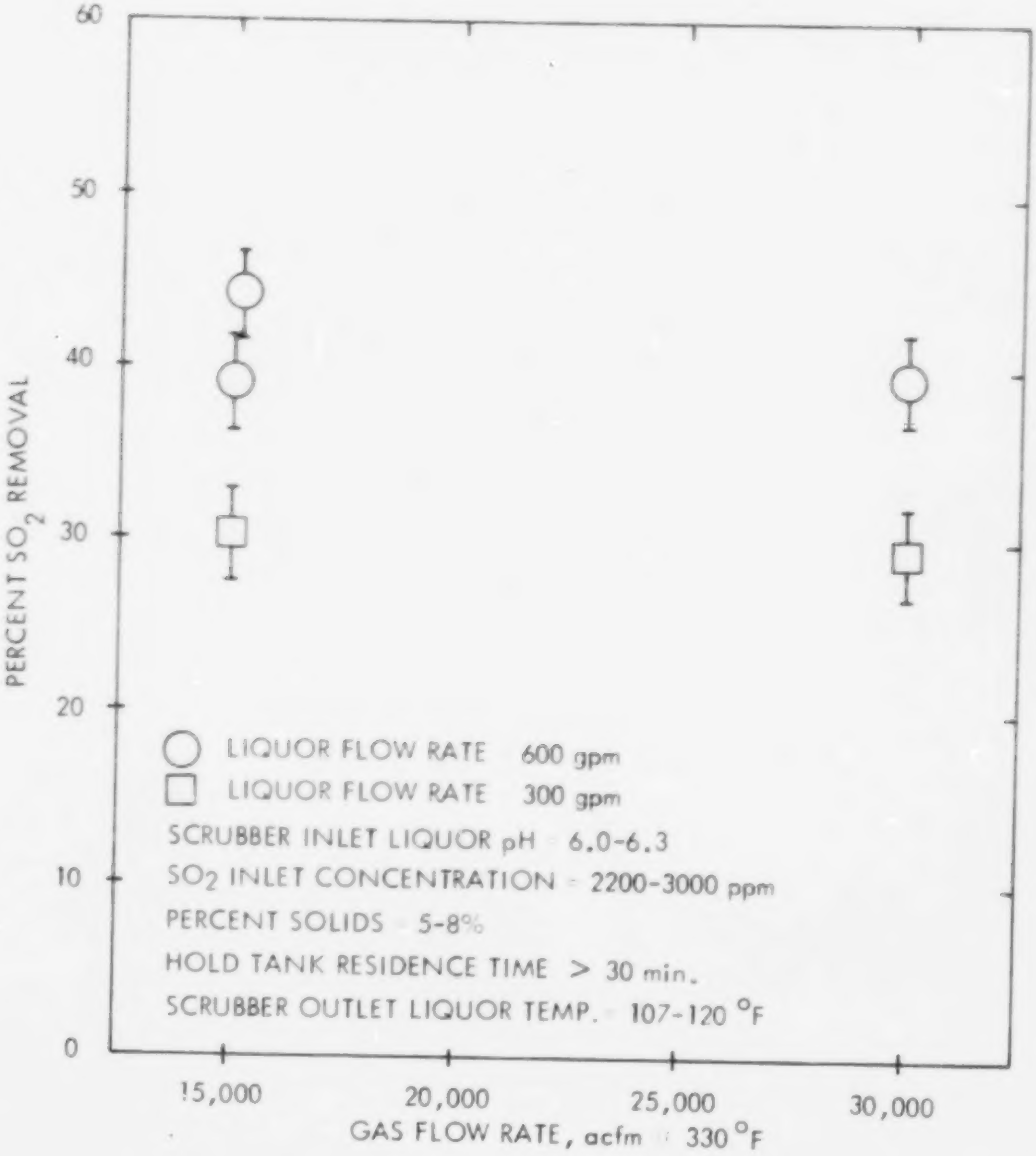

Figure 6-1. Effect of Gas and Liquor Flow Rates on SO_2 Removal in the Chemico Venturi with Nine Inches of Pressure Drop

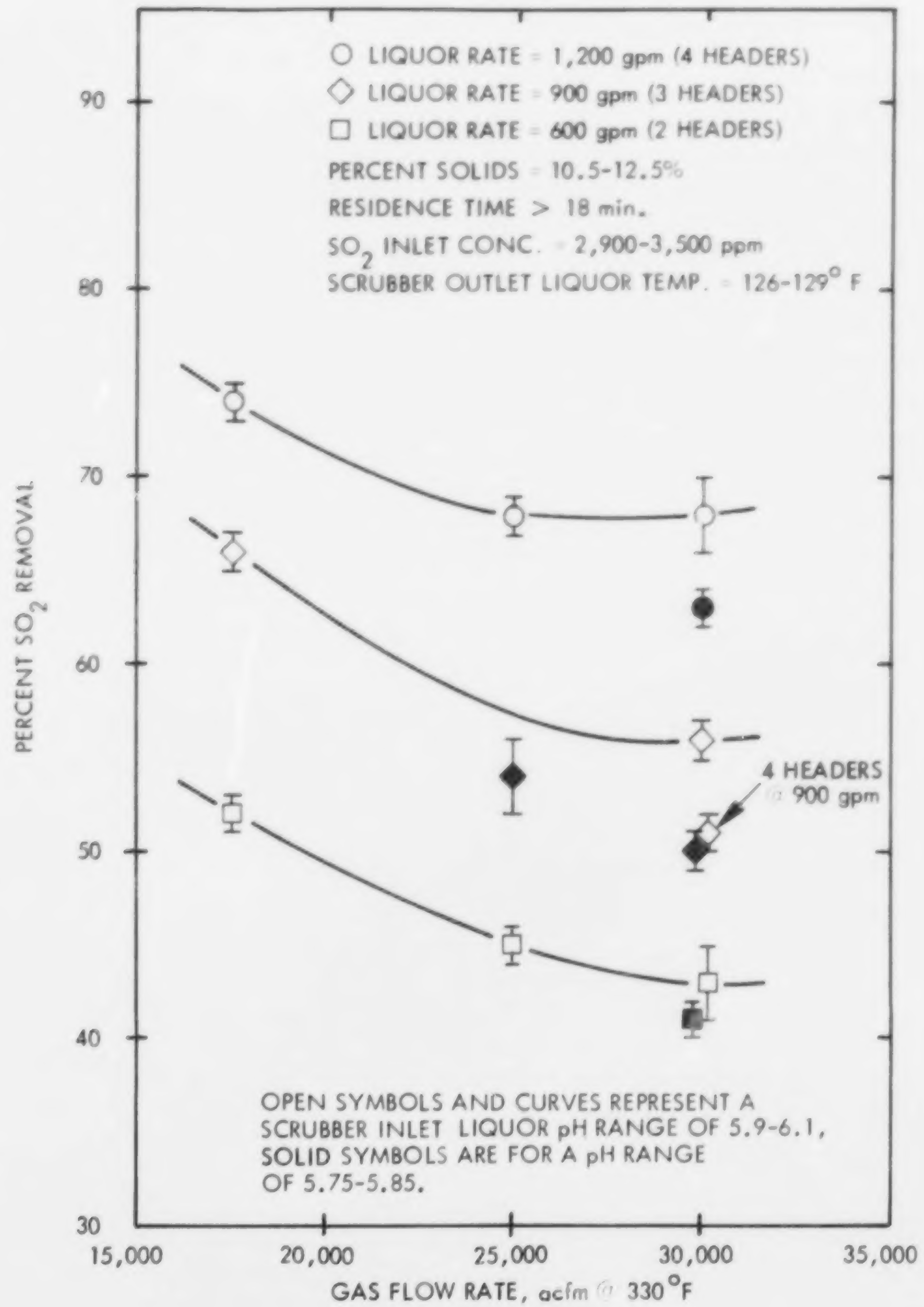

Figure 6-2. Effect of Gas and Liquor Flow Rates on SO_2 Removal in the Spray Tower

Figure 6-3 is a cross-plot of Figure 6-2, showing the effect of liquid-to-gas ratio and gas velocity on SO_2 removal for an inlet liquor pH of approximately 6.0. The effect of liquid-to-gas ratio on SO_2 removal (for a gas velocity of 8.0 ft/sec) at liquor inlet pH ranging from approximately 6.0 to 5.8 is shown in Figure 6-4.

6.1.3 TCA Scrubber (Table E-2, Appendix E)

The results of the EPA TCA limestone runs are summarized in Figures 6-5 through 6-7.*

Figure 6-5 shows the effects of spheres versus no spheres and gas flow rate on SO_2 removal in the six-grid,** three-bed TCA system. The data indicate that SO_2 removal is significantly affected by the presence of the spheres and is only slightly affected by gas rate within the region investigated.

The liquor and gas rate effects on SO_2 removal in the four-grid, three-bed TCA system are presented in Figure 6-6. As shown from this data,

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* From November 4, 1972, to January 15, 1973, TVA conducted a special series of tests with the TCA scrubber to provide process and equipment scale-up and design information for the 550 Mw coal-fired TVA Widows Creek Unit 8 retrofit limestone scrubbing system. The results shown on Figures 6-5 through 6-7 do not include the TVA tests.

** For the six-grid, three-bed configuration, spheres were placed between the first and second, third and fourth, and fifth and sixth grids. Subsequent to the initial factorial testing of the TCA in the six-grid configuration, all testing has been done with the TCA in the "normal" four-grid, three-bed configuration (see Figure 3-2).

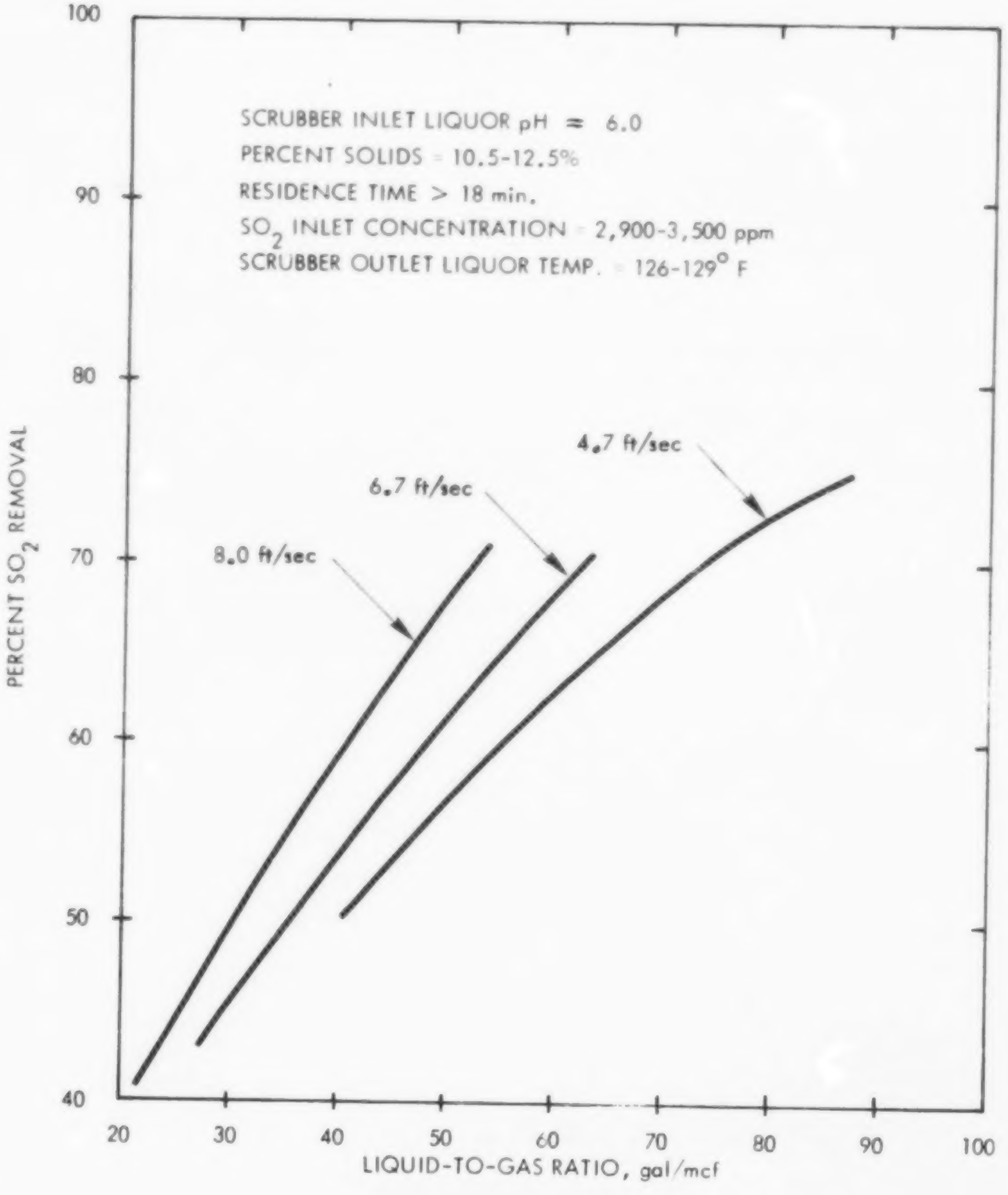

Figure 6-3. Effect of Liquid-to-Gas Ratio and Gas Velocity on SO_2 Removal in the Spray Tower

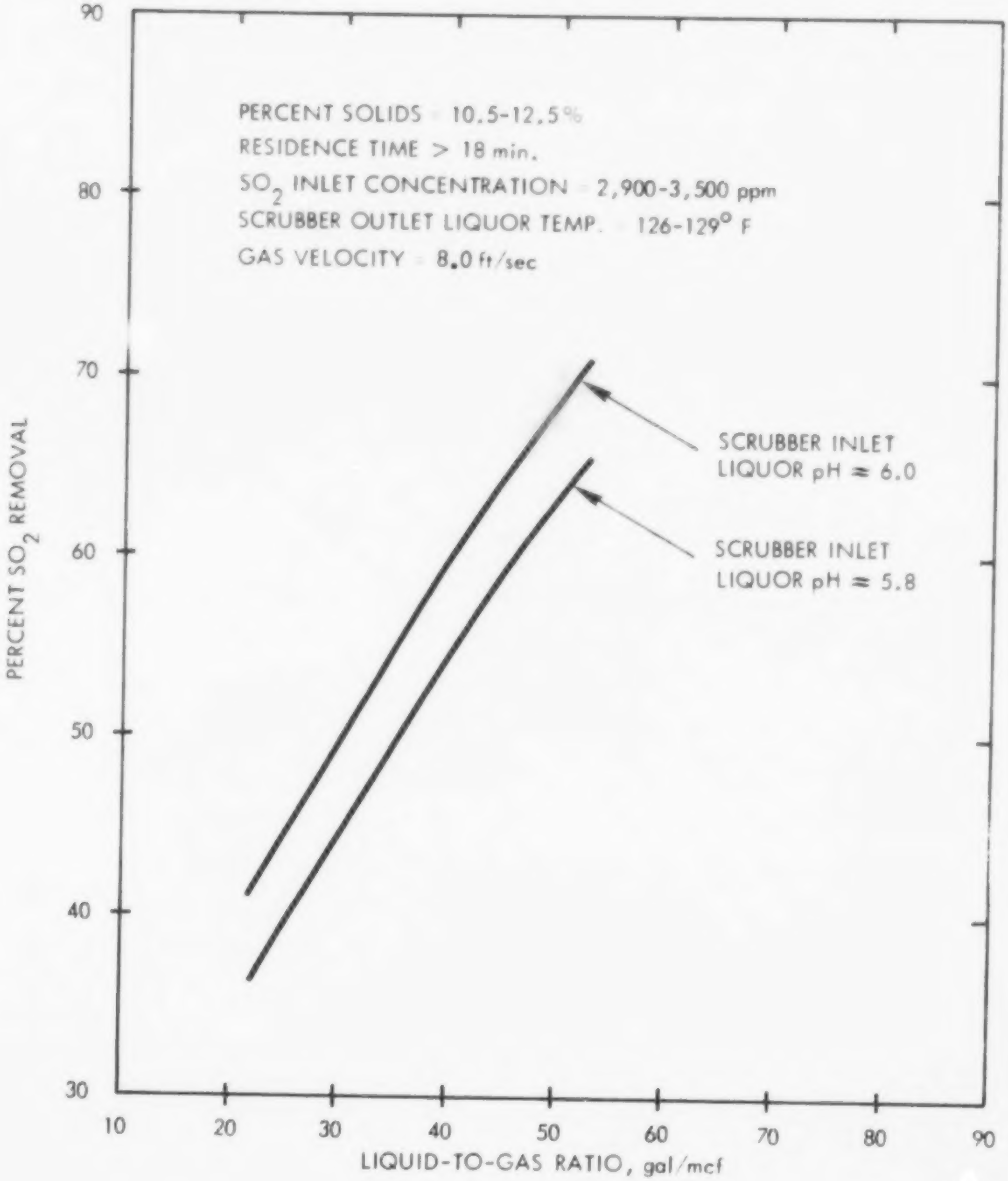

Figure 6-4. Effect of Scrubber Inlet Liquor pH and Liquid-to-Gas Ratio on SO_2 Removal in the Spray Tower at 8.0 ft/sec Gas Velocity

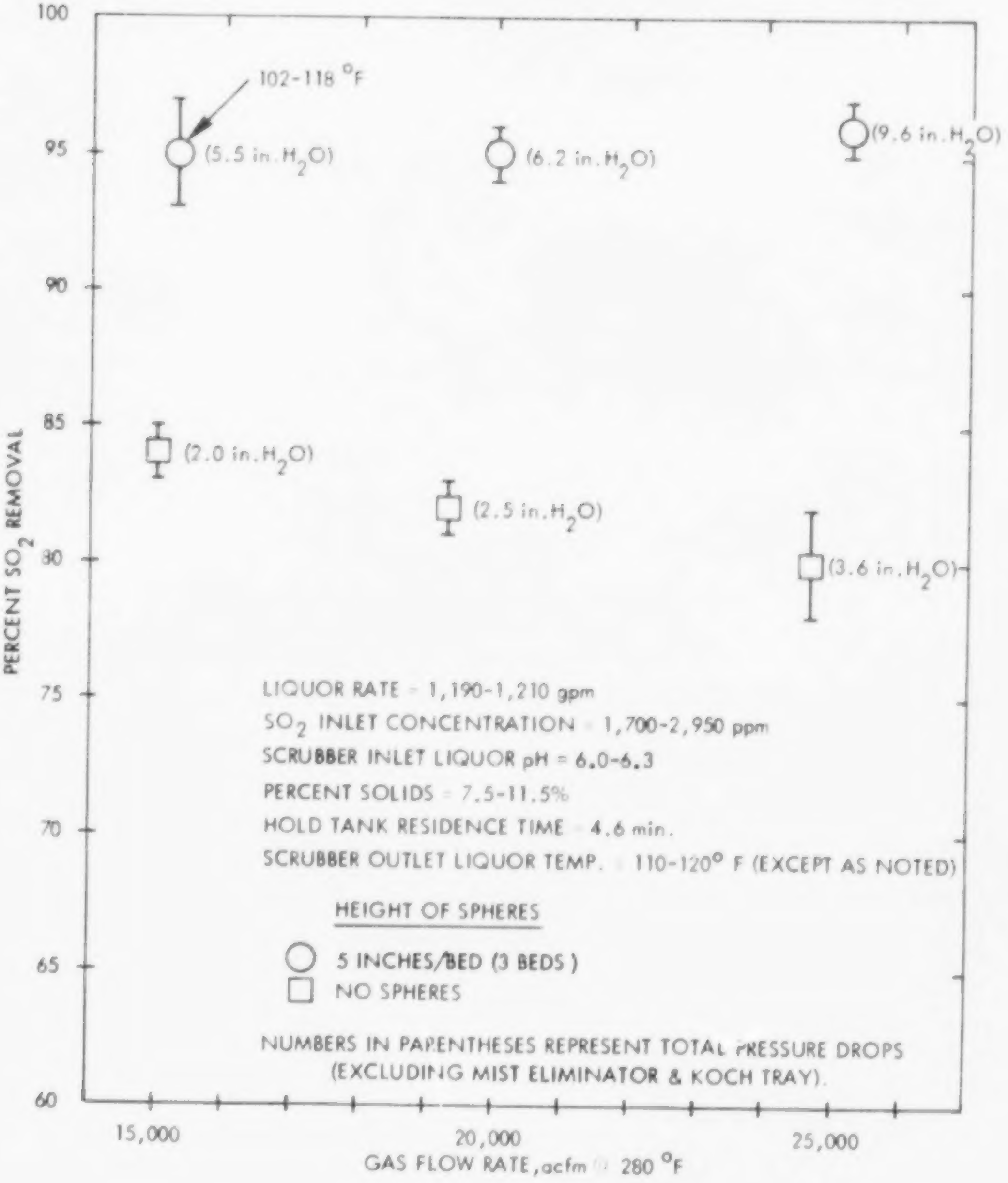

Figure 6-5. Effect of Spheres versus no Spheres and Gas Flow Rate on SO_2 Removal in the Six-Grid, Three-Bed TCA

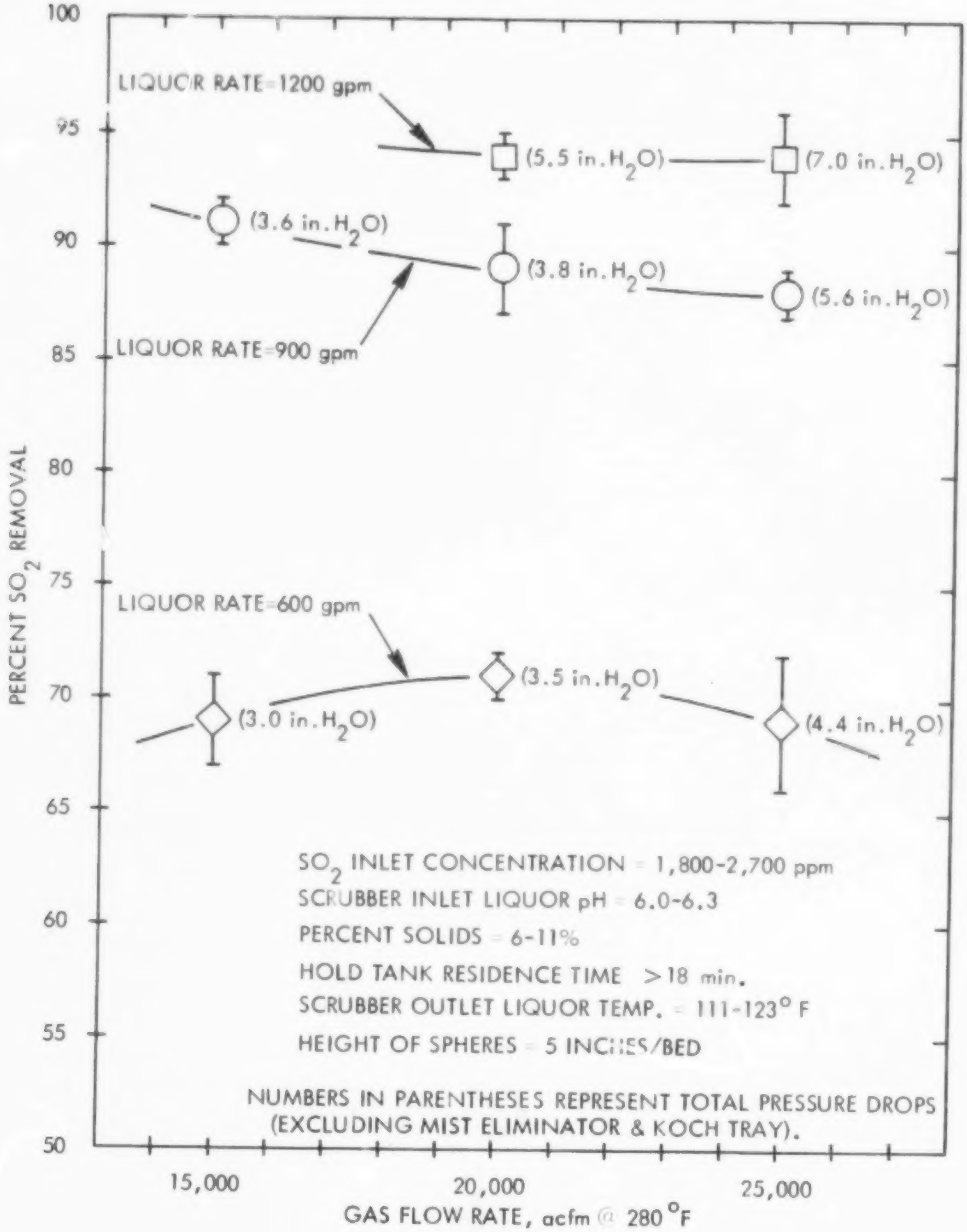

Figure 6-6. Effect of Gas and Liquor Flow Rates on SO_2 Removal in the Four-Grid, Three-Bed TCA

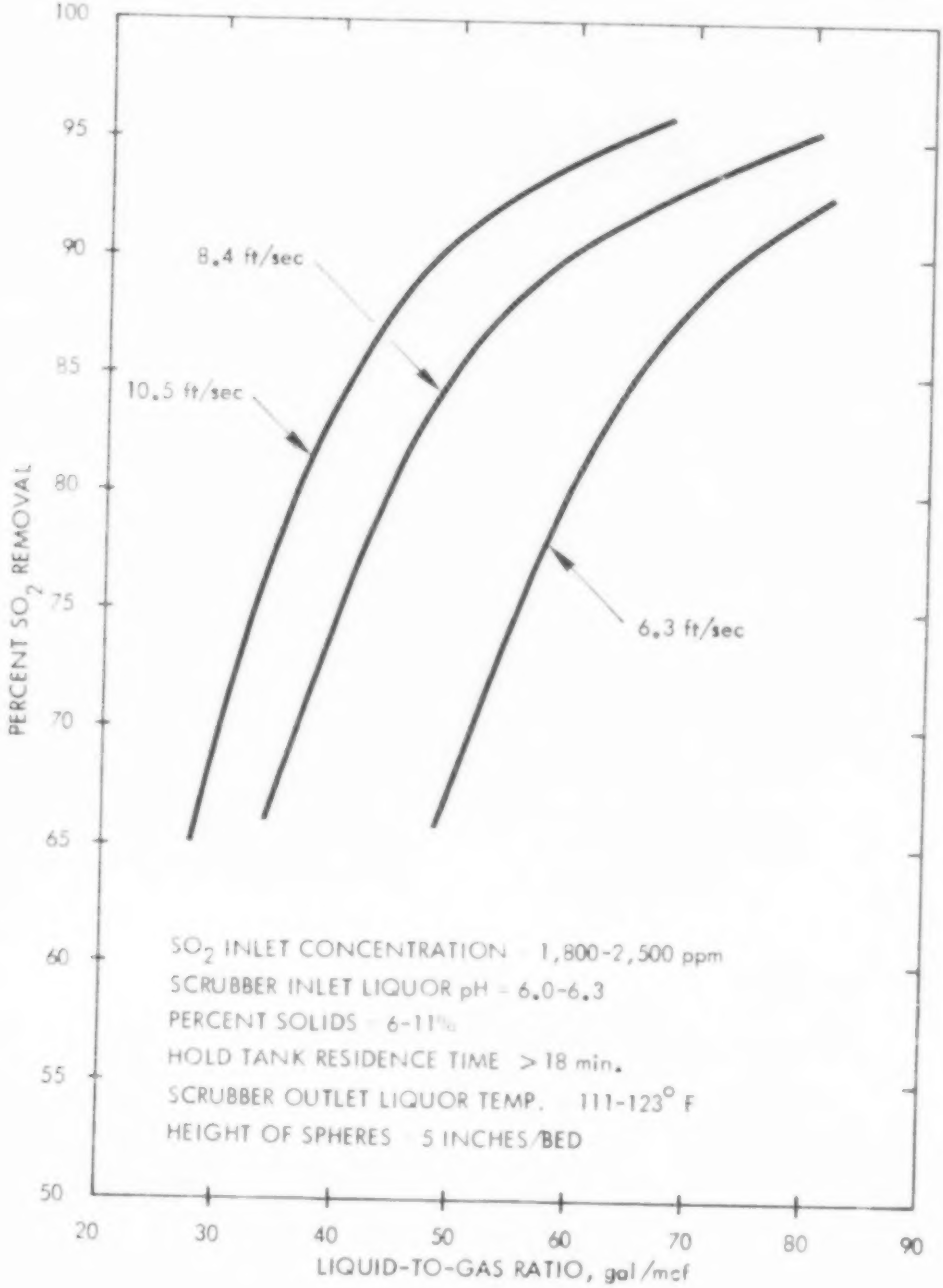

Figure 6-7. Effect of Liquid-to-Gas Ratio and Gas Velocity on SO$_2$ Removal in the Four-Grid, Three-Bed TCA

SO_2 removal is a significant function of liquor rate and is only slightly affected, if at all, by gas rate within the region investigated. Figure 6-7 is a cross-plot of Figure 6-6 showing the effect of liquid-to-gas ratio and gas velocity on SO_2 removal.

6.1.4 Marble-Bed Scrubber

Figure 6-8 shows the effect of gas and liquor flow rates on SO_2 removal in the Marble-Bed system with five inches of marble-bed height. The data indicate that SO_2 removal is a function of liquor rate but is only slightly affected, if at all, by gas velocity within the region investigated. Figure 6-9 is a cross-plot of Figure 6-8 showing the effect of liquid-to-gas ratio and gas velocity on SO_2 removal.

6.2 ANALYTICAL RESULTS

As mentioned previously, a majority of the limestone factorial tests with the three scrubber systems were made during open liquor loop operation.* The average concentration of total dissolved solids in the scrubber inlet liquor during these tests was about 3800 ppm. The average species concentrations were: 1000 ppm Ca^{++}, 70 ppm Mg^{++}, 40 ppm Na^+, 50 ppm K^+, 250 ppm $SO_3^=$, 1200 ppm $SO_4^=$, 100 ppm $CO_3^=$, and 1100 ppm Cl^-. The chlorides in the liquor are attributable to chlorides present in the coal which are converted to HCl and absorbed from the flue gas.

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*Analytical data for closed liquor loop limestone testing are presented in Sections 7 and 8.

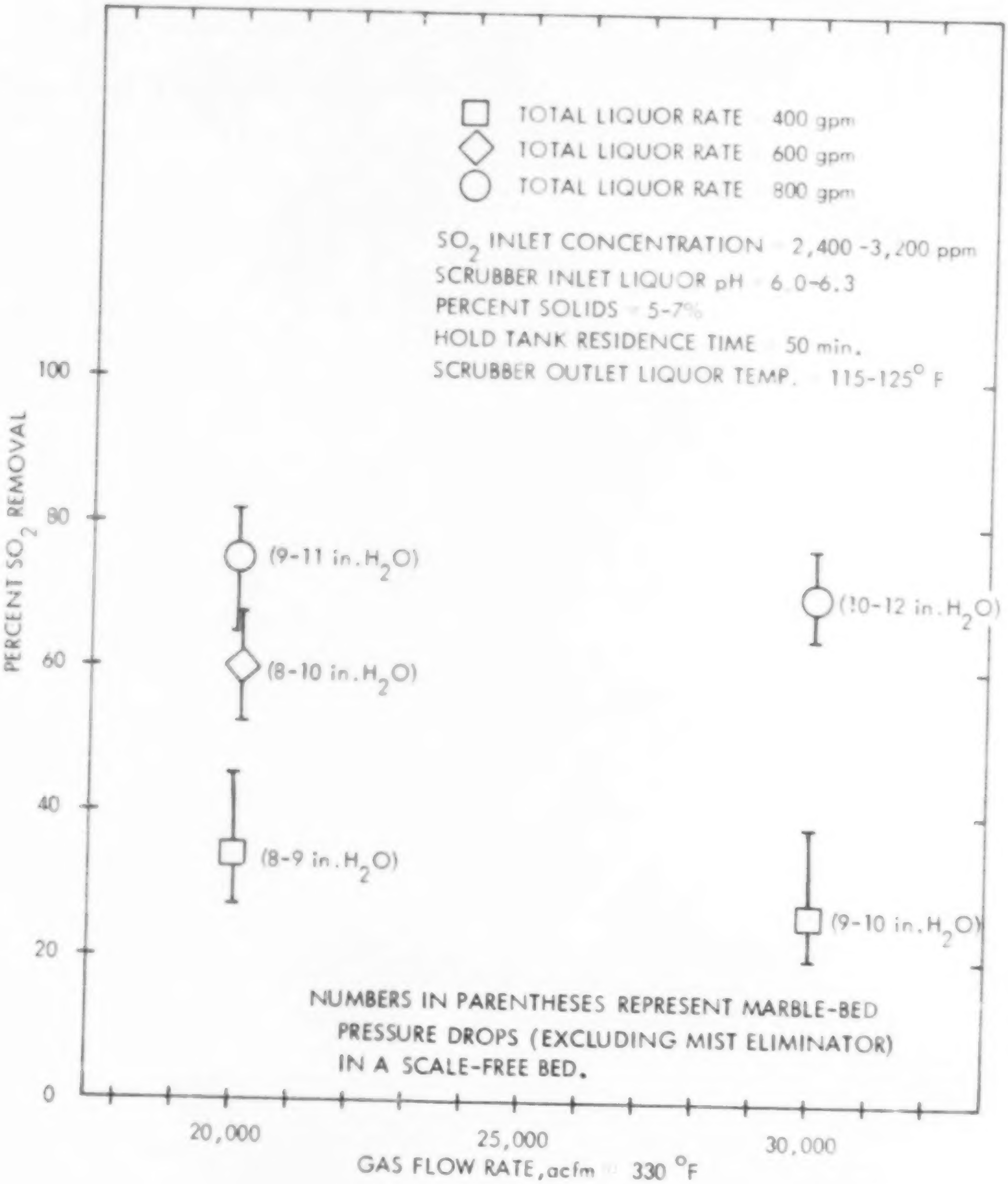

Figure 6-8. Effect of Gas and Liquor Flow Rates on SO_2 Removal in the Marble-Bed Scrubber with Five Inches of Marbles

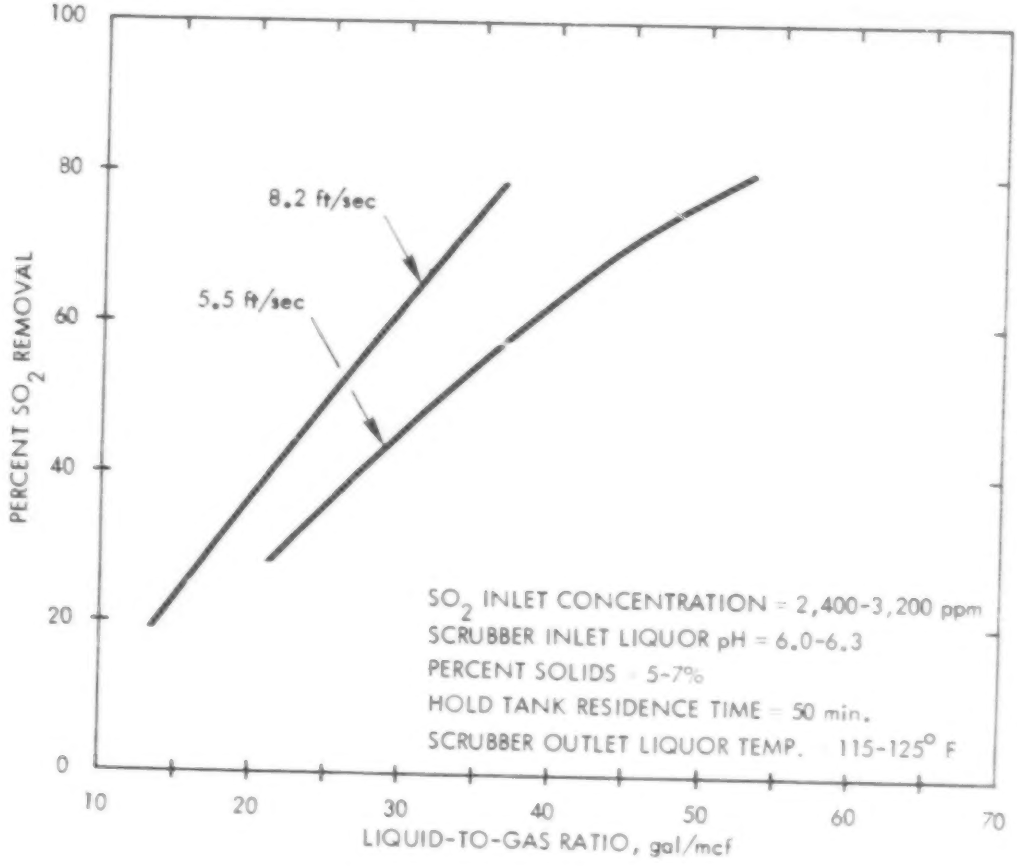

Figure 6-9. Effect of Liquid-to-Gas Ratio and Gas Velocity on SO_2 Removal in the Marble-Bed Scrubber with Five Inches of Marbles

The composition of solids in the slurry is fixed by the moles $CaCO_3$ added per mole SO_2 absorbed (stoichiometric ratio), the overall percent oxidation of sulfite to sulfate within the system, and the percent of fly ash. The mole percent oxidations averaged approximately 30 percent during the open liquor loop factorial testing and the fly ash comprised from 30 to 50 wt % of the solids for the scrubber systems.

Section 7

LIMESTONE RELIABILITY VERIFICATION TEST RESULTS

Performance data from limestone reliability verification testing at the Shawnee facility are presented in this section, along with an evaluation of each reliability verification test. Operating experience associated with specific system components (e.g., mist eliminators, reheaters, SO_2 gas analyzers) will be discussed in detail in Section 10. Properties of coal and limestone used during these tests can be found in Appendix C.

As part of the analysis of the data, the scaling potential of scrubber internals has been correlated with the calculated scrubber liquor sulfate (gypsum) saturation. This is discussed in Section 7.3.

7.1 RELIABILITY VERIFICATION PERFORMANCE DATA

The major objective of the closed liquor loop limestone reliability verification tests was to identify areas or regions for reliable long term (4 to 6 months) operation consistent with reasonable SO_2 removal.

A majority of the reliability verification tests were on-stream for approximately 500 hours (3 weeks). It should be noted that it is difficult to assess long-term reliability from runs lasting 500 hours, especially when small quantities of scale[*] or soft solids are present on system components.

Summaries of the limestone reliability verification test results for the venturi/spray tower, TCA, and Marble-Bed systems are presented in Tables 7-1, 7-2, and 7-3 and evaluated in Tables 7-4, 7-5, and 7-6, respectively. Complete operating data for selected Runs 506-1A (venturi/spray tower), 510-2A (TCA), and 506-3B (Marble-Bed) are graphically presented in Appendix F.

The major system problems addressed at the test facility are associated with scaling and plugging of the equipment. A majority of the component problems can be solved by improved design. The major variables affecting scaling and plugging tendencies are: (1) effluent residence time, (2) percent solids recirculated, (3) percent oxidation of sulfite to sulfate, (4) gas velocity, (5) liquid-to-gas ratio, (6) scrubber pH, and (7) concentration of solids in the discharge sludge.

The limestone reliability verification tests were run at reduced scrubber inlet liquor pH (5.6 to 5.9) to decrease the potential for sulfite scaling and to increase limestone utilization. A modest reduction in SO_2 removal, from high-pH[**] performance, is the price of the increased system reliability and limestone utilization.

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[*] In this report "scale" refers only to crystalline hard solids, and "solids" or "soft-solids" refer to mud-like slurry solids. "Plugging" refers to the accumulation of mud-like slurry solids. Also, scale refers to sulfate base scale, unless otherwise noted.

[**] The limestone short-term factorial tests were run at a scrubber inlet liquor pH range from 6.0 to 6.3 (see Section 6).

The test conditions for the initial reliability verification runs were selected in order to give maximum probability for reliable operation consistent with reasonable SO_2 removal. Subsequent tests were made to observe the effects of reduced effluent residence time, reduced percent solids recirculated, increased gas velocity (at constant liquor rate), and increased scrubber inlet liquor pH on system reliability.[*] In addition, the effects of mist eliminator type (polypropylene vs. stainless) and mist eliminator wash location (bottomside vs. combined bottomside and topside washing) were investigated in the venturi/spray tower system.

7.1.1 Venturi/Spray Tower System

Results of the venturi/spray tower reliability verification tests are reported in Table 7-1 and evaluated in Table 7-4. The initial venturi/spray tower test Run 501-1A was conducted, as mentioned previously, under conditions selected to maximize the probability for reliable operation (i.e., an effluent residence time of 20 minutes, a percent solids recirculated of 15-16 percent,[**] and a spray tower gas velocity of 5.4 ft/sec). As expected, the relative condition of the system at the end of the test was good. Subsequent venturi/spray tower runs were made at more economically attractive operating conditions. Run 507-1A indicated relatively good system condition at the end of 434 operating hours

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[*] Minimizing effluent residence time and percent solids recirculated and maximizing gas velocity is, of course, economically attractive.

[**] Approximately 40 percent of solids is fly ash.

Table 7-1

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: VENTURI/SPRAY TOWER SYSTEM

Run No.	501-1A	502-1A	503-1A	506-1A
Test Objectives	Reliability verification test @ low pH with Chevron 316 S.S. mist eliminator.	Same as 501-1A with Chevron plastic mist eliminator.	Same as 502-1A with higher liquor rate and lower percent solids recirculated.	Same as 503-1A with higher gas rate and lower effluent residence time. Top and bottom mist elim. wash.(e)
Start-of-Run Date	4/9/73	6/13/73	6/29/73	7/25/73
End-of-Run Date	5/9/73	6/26/73	7/11/73	8/13/73
On Stream Hours(a)	645	278	256	417
Gas Rate, acfm @ 330°F	20,000	20,000	20,000	30,000
Spray Tower Gas Vel., fps @125°F	5.4	5.4	5.4	8.0
Venturi/Spray Tower Liquor Rates, gpm	600/600	600/600	600/1200	600/1200
Spray Tower L/G, gal/mcf	37	37	75	50
Percent Solids Recirculated	15-16	14-16	8-9	8-10.5
Effluent Residence Time, min.	20	20	20	12
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.4-1.6(4/9-4/27) 1.9-2.1(4/27-5/9)(d)	1.5-1.9	1.4-1.6	1.4-1.6 (1.6-1.8 from 8/3-6)(f)(g)
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	67 (4/9-4/27) 50(4/27-5/9) (d)	59	67	67 (59 from 8/3 to 8/6)(f)(g)
Inlet SO_2 Concentration, ppm	2,400-3,300	2,200-3,000	2,200-3,000	2,500-3,300 (2,000-2,200 on 7/26 & 28)
Percent SO_2 Removal	70-75	67-73	74-82	68-76
Scrubber Inlet pH Range	5.8-6.0	5.7-5.9	5.6-5.8	5.35-5.65
Scrubber Outlet pH Range	5.4-5.7	5.3-5.5	5.1-5.3	4.85-5.1
Percent Sulfur Oxidized	5-25	15-35	20-40	20-35
Solids Disposal System	Clarifier	Clarifier	Clarifier	Clarifier and centrifuge
Loop Closure, % Solids Disch.	20-28	21-39	27-41	55-65
Clear Liquor to Mist Elim., gpm	14-20	14-20	27-33	40-55
Make-Up Water to Mist Elim., gpm	12-14	12-14	10-12	8-11
Dissolved Solids, ppm	5,000-8,000	-	7,300	14,900 (i)
Total ΔP Range, in. H_2O(b)	10-11	10.0-10.5	10.4-11.6	12.5-14.5
Mist Elim ΔP Range, in. H_2O	0.40-0.65	0.40-0.55	0.45-0.55	1.0-1.25 (h)
Mist Eliminator Condition at End of Run (c) (e)	Scattered 1/8" scale on top and 20 mil scale on bottom.	1/16" scale on top. Light scale and solids between vanes. Approximately 1/3 ft^3 solids buildup at 4 locations (junction of support bars).	No scale or solids on top. 1/2 to 1" non-uniform scattered solids deposit on top of bottom vane and on 2nd pass of vane. Center portions clean.	Some plastic vanes damaged by chunks of solids broken off from outlet duct. 5 mil solids buildup on westside vanes. Moderate solids buildup on dead spots on support I beams & adjacent vanes.
Venturi and Spray Tower Conditions at End of Run	Thin scattered scale and eroded guidevane bolts in venturi section. Scattered 15-25 mil scale on after-scrubber walls above trapout tray. 9 of 28 slurry ST48FCN spray nozzles in after-scrubber were plugged.	5 mil scale on walls below plug and about 1/6 bolts heads on guidevanes in venturi section eroded. 10 mil scale on after-scrubber walls below trapout tray.	20 mil scale on walls below plug and noticeable erosion of guidevane cross braces in venturi section. 15 mil scale on after-scrubber walls below trapout tray. 3 of 28 slurry spray nozzles plugged.	15 mil scale on walls of flooded elbow & below plug. Cont'd erosion of guidevane cross braces. 20 mil light scattered scale on after-scrubber walls & spray headers. No signif. solids accum. above & below trapout tray. Severe solids deposits in reheater outlet duct.

(a) Includes line-out.

(b) Spray tower and venturi, excluding mist eliminator.

(c) Chevron plastic four-pass open mist elim. in all runs except 501-1A where Chevron 316 S.S. three-pass open mist eliminator was used.

(d) Reactivity of limestone decreased after 4/27 due to larger average limestone particle size.

(e) Mist elim. was washed from bottom only for all runs except Run 506-1A where it was washed from both top and bottom.

(f) The stoichiometry range was higher at 1.6-1.8 (59% average limestone utilization) from 8/3 to 8/6 with correspondingly higher scrubber inlet pH range of 5.5 to 5.65.

(g) As of 7/27, a new limestone containing approx. 1.25 mole % $MgCO_3$ was used. Prior to this time a limestone having approx. 5 mole % $MgCO_3$ had been used.

(h) Range given is for period 7/25-8/8. Increased steadily from 1.25 to 1.40 in. H_2O after 8/8.

(i) Increasing steadily during run from 8,000 to 14,900 ppm.

Table 7-1 (continued)

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: VENTURI/SPRAY TOWER SYSTEM

Run No.	507-1A	508-1A[h]	
Test Objectives	Same as 506-1A with chevron 316 S.S. mist elim. with bottom wash only.	Same as 507-1A with top and bottom mist eliminator wash.	
Start-of-Run Date	8/22/73	9/11/73	
End-of-Run Date	9/9/73	9/12/73	
On Stream Hours[a]	434	28	
Gas Rate, acfm @ 330° F	30,000	30,000	
Spray Tower Gas Vel., fps @125°F	8.0	8.0	
Venturi/Spray Tower Liquor Rates, gpm	600/1200	600/1200	
Spray Tower L/G, gal/mcf	50	50	
Percent Solids Recirculated	8-10.5	10.5-11.5	
Effluent Residence Time, min.	12	12	
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.2-1.4 (1.4-1.75 from 8/31 to 9/7)[d]	1.3-1.5	
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	77 (63 from 8/31 to 9/7)[d]	71	
Inlet SO_2 Concentration, ppm	2,400-3,400 (1,400-1,750, 8/31-9/3)	2,600-3,700	
Percent SO_2 Removal	67-77	70-74	
Scrubber Inlet pH Range	5.3-5.65	5.65-5.85	
Scrubber Outlet pH Range	4.9-5.2	5.5	
Percent Sulfur Oxidized	25-45[f]	20-28	
Solids Disposal System	Clarifier and centrifuge[e]	Clarifier	
Loop Closure, % Solids Disch.	53-68[e]	19	
Clear Liquor to Mist Elim., gpm	46-60[g]	33-57	
Make-Up Water to Mist Elim., gpm	6-11[g]	14-20	
Dissolved Solids, ppm	16,300-18,800[e]	–	
Total ΔP Range, in. H_2O[b]	13.5-14.5	13.5-14.0	
Mist Elim. ΔP Range, in. H_2O	1.25-1.35	1.3-1.4	
Mist Eliminator Condition at End of Run[c]	5 mil solids deposit on all bottom vanes & 10 mil on all top vanes. In NE section: 2 ft^2 area 75% plugged (top), another 2 ft^2 25% plugged (top).	Approximately the same condition as at end of run 507-1A.	
Venturi and Spray Tower Conditions at End of Run	Venturi operated without sootblower. 3-4" solids deposit on E&W quadrant of inlet duct walls upstream of plug & on bull nozzle feed pipe. < 5 mil scale on walls of venturi below plug & on flooded elbow.	Approximately the same condition as at end of run 507-1A, except heavy solids build-up in reheater outlet duct.	

(a) Includes line-out.

(b) Spray tower and venturi, excluding mist eliminator.

(c) Chevron 316 S.S. three-pass open mist elim. was used.

(d) High stoichiometry range of 1.4-1.75 (63% average limestone utilization) caused by excess limestone in scrubber slurry during the period of low inlet SO_2 concentration (av. 1600 ppm) from 8/31 through 9/3.

(e) Switched to clarifier only at 0930 hours on 8/31. Percent solids discharged was 20-30 wt. % and dissolved solids decreased gradually to 11,300 ppm (on 9/6) after 8/31.

(f) 50-75% oxidation from 8/31 through 9/3 when average inlet SO_2 concentration dropped to 1600 ppm.

(g) The flow ranges for clear liquor and makeup water were 34-53 and 15-21 gpm, respectively, from 8/31 to 9/9, when clarifier only was used.

(h) System shut down after 28 hours of operation due to system problems (i.e., high entrainment from mist elim. top flush, pluggage of outlet Du Pont SO_2 analyzer sample probes).

Table 7-2

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: TCA SYSTEM

Run No.	501-2A	502-2A	508-2A	509-2A
Test Objectives	Reliability verification test @ low pH.	Same as 501-2A with high stoichiometry and pH.	Replicate of 501-2A.	Same as 501-2A with lower percent solids recirc.
Start-of-Run Date	3/22/73	4/27/73	5/25/73	6/5/73
End-of-Run Date	4/23/73	5/21/73	5/29/73	6/25/73
On Stream Hours[a]	580	557	98	465
Gas Rate, acfm @ 300°F	20,000	20,000	20,000	20,000
Gas Velocity, fps @ 125°F	8.3	8.3	8.3	8.3
Liquor Rate, gpm	1200	1200	1200	1200
L/G, gal/mcf	75	75	75	75
Percent Solids Recirculated	14-16	14-16	15-16	8-9
Effluent Residence Time, min.	20	20	20	20
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.1-1.4	1.5-1.9 (2.1-2.7 from 5/5-12)[c]	1.2-1.4	1.2-1.45
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	80	59 (42 from 5/5-12)[c]	77	75
Inlet SO_2 Concentration, ppm	2,200-3,300	2,300-3,300	2,300-3,000	2,000-3,100
Percent SO_2 Removal	80-86	90-97	82-87	80-88
Scrubber Inlet pH Range	5.6-6.0	5.9-6.1	5.6	5.5-5.8
Scrubber Outlet pH Range	5.1-5.7	5.4-5.7	5.0-5.2	5.0-5.4
Percent Sulfur Oxidized	20-40	17-35	20-35	32-50
Solids Disposal System	Clarifier	Clarifier	Clarifier	Clarifier
Loop Closure, % Solids Disch.	25-48	31-39	31-43	26-45
Clear Liquor to Koch Tray, gpm	20-30	5-20	5-18	20-45
Make-Up Water to Koch Tray, gpm	7-12	8-12	7-12	7-11
Dissolved Solids, ppm	4,000-10,000	4,300-8,800	–	8,300-11,800
Total ΔP Range, in. H_2O[b]	4.5-5.3	5.5-6.5[d]	5.0-6.0	5.0-5.8
Mist Eliminator and Koch Tray ΔP Range, in. H_2O	1.6-2.0	1.9-2.2	1.9-2.1	1.9-2.0
Mist Eliminator Condition at End of Run	1/16" scale on bottom vanes only.	1/16" scale on vanes. About 50% of west quadrant plugged.	Clean.	1/16" scale on west quadrant.
Bed Condition at End of Run	Spheres in middle bed fell down to lower bed due to 2 holes in bottom grid. Replaced 3 dozen collapsed spheres.	No grid failure but significant deterioration of grid wire continued.	Replaced about 5% of collapsed spheres. Replaced 3 damaged grid sections.	Replaced the damaged SW section of top grid. Replaced about 20% of collapsed spheres.
Inlet Duct Condition at End of Run	Slight solids built-up upstream and heavy solids buildup downstream of cooling nozzles.	About 60% of duct area plugged. Solids buildup at and upstream of nozzles.	Solids buildup upstream of cooling nozzles.	Clean.
Other Problems or Comments	9 intermediate shutdowns due to cooling nozzle and Ventri-Rod pluggage. Ventri-Rod pluggage ranged from 12-70%. Replaced Ventri-Rod with 4 ST24FCN SS Bete nozzles on 4/16/73.	4 intermediate shutdowns due to cooling nozzles pluggage. Used Spraco 71B 316 SS nozzles on 5/5/73.	–	Modified soot-blower head on 5/29/73 to have 2 jets blowing air forward only. Capped bottom cooling spray nozzle.

(a) Includes line-out.

(b) Total, excluding mist eliminator and Koch Tray.

(c) Reactivity of limestone decreased during the period of higher stoichiometry range and lower average limestone utilization, due to larger average limestone particle size.

(d) Range given is for period before 5/15. Increased gradually from 6 to 9 in. H_2O from 5/15 to 5/21.

Table 7-2 (continued)

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: TCA SYSTEM

Run No.	510-2A	514-2A	515-2A	
Test Objectives	Same as 509-2A with higher gas rate.	Same as 510-2A with lower effluent residence time and higher percent solids recirculated.	Same as 514-2A with lower percent solids recirculated.	
Start-of-Run Date	6/27/73	7/22/73	8/16/73	
End-of-Run Date	7/10/73	8/13/73	9/10/73	
On Stream Hours(a)	297	493	571	
Gas Rate, acfm @ 300°F	25,000	25,000	25,000	
Gas Velocity, fps @ 125°F	10.5	10.5	10.5	
Liquor Rate, gpm	1200	1200	1200	
L/G, gal/mcf	60	60	60	
Percent Solids Recirculated	7.5-9.5	13.5-16	7.0-8.5	
Effluent Residence Time, min.	20	4.4	4.4	
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.2-1.5	1.25-1.55(7/22-8/5) 1.15-1.3(8/6-13)(g)	1.2-1.4(1.4-1.55 from 8/31 to 9/3)(c)	
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	74	71 (7/22-8/5) 82 (8/6-13)(g)	77 (68 from 8/31 to 9/3)(c)	
Inlet SO_2 Concentration, ppm	2,000-2,700	2,100-3,100(1,800-2,100, 7/24, 26 & 28)	2,400-3,300(1,450-1,700, 8/31-9/3)	
Percent SO_2 Removal	78-89	77-89	80-88	
Scrubber Inlet pH Range	5.4-5.5	5.2-5.55	5.2-5.4	
Scrubber Outlet pH Range	4.85-5.2	4.7-5.0	4.9-5.1	
Percent Sulfur Oxidized	35-55	20-50	25-50(d)	
Solids Disposal System	Clarifier	Clarifier	Clarifier(e)	
Loop Closure, % Solids Disch.	26-44	27-52	34-44(e)	
Clear Liquor to Koch Tray, gpm	25-45	5-26	36-50	
Make-Up Water to Koch Tray, gpm	9-13	9-13	10-12	
Dissolved Solids, ppm	8,800-11,300	4,800-11,400	11,000-13,300(f)	
Total ΔP Range, in. H_2O(b)	6.6-7.6	7.0-8.5	7.0-8.5	
Mist Eliminator and Koch Tray ΔP Range, in. H_2O	2.2-2.5	2.2-2.5(2.5-2.8 from 8/10 to 8/13)	2.2-2.5(2.5-2.9 from 9/6 to 9/10)	
Mist Eliminator Condition at End of Run	60 mil scale on most of mist elim. 3 of 14 sections in SW corner were partially plugged with 1/2" solids between bottom vanes.	20% area plugged with solids. NW quadrant had higher buildup (50% plugged) with hard cryst. solids. Solids buildup mainly on bottom vanes. Pitting continued.	40% area plugged. Solids buildup mainly on bottom 2 vanes. Up to 1" solids buildup on underside of Koch tray. Tray valves partially plugged.	
Bed Condition at End of Run	Several loose grid wires. No grid replacement needed.	14% damaged spheres in lower 2 beds. Light scale on 75% of bottom grid.	Broken grid wires.(h) (2-3" stalactite on btm. grid. 1/32-1/16" scale on walls.	
Inlet Duct Condition at End of Run	Clean.	7 ft^3 solids buildup upstream of nozzles.	Clean.	
Other Problems or Comments	–	As of 7/27 a new limestone having ~ 1.25 mole % $MgCO_3$ was used. Prior to this time, limestone containing ~ 5 mole % $MgCO_3$ was used.	Underside of Koch tray not properly washed due to loose steam sparger branch headers.	

(a) Includes line-out.

(b) Total, excluding mist eliminator and Koch Tray.

(c) High stoichiometry range of 1.4-1.55 (68% average limestone utilization) caused by excess limestone in scrubber slurry during the period of low inlet SO_2 concentration (av. 1600 ppm) from 8/31 through 9/3.

(d) 48-80% oxidation from 8/31 through 9/3 when average inlet SO_2 concentration dropped to 1600 ppm.

(e) With clarifier and centrifuge before 1235 hours on 8/20. Percent solids discharged from centrifuge was 58-59%.

(f) No analytical data before 8/20, when clarifier and centrifuge were used.

(g) Indicates effect of utilization of new limestone (see Other Problems or Comments).

(h) About 6 in^2 of support grid for top bed broken. Some of top bed spheres dropped into middle bed.

Table 7-3

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: MARBLE-BED SYSTEM

Run No.	501-1A & 1B	502-1A	503-1A & 1B	504-1A & 505-1A
Test Objectives	Reliability verification test @ low pH.	Same as 501-1A & 1B with high stoichiometry & pH.	Same as 501-1A & 1B with lower percent solids recirc.	Same as 501-1A & 1B with Spraco bed spray nozzles.
Start-of-Run Date	3/14/73	4/25/73	5/11/73	7/25/73
End-of-Run Date	4/23/73	5/7/73	5/22/73	[illegible]4/73
On Stream Hours[a]	771	285	267	211
Gas Rate, acfm @ 330°F	20,000	20,000	20,000	20,000
Gas Velocity, fps @ 125°F.	5.4	5.5	5.5	5.5
Liquor Rates to Top/Bottom Sprays, gpm	200/600	200/600	200/600	200/600
L/G, gal/mcf	50	50	50	50
Percent Solids Recirculated	10-12	11-14	8-11	10-12
Effluent Residence Time, min.	40	40	40	40
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.15-1.45(3/14-4/7) 1.3-1.6 (4/8-23)[g]	1.5-2.1 (4/25-29) 1.9-2.7(4/29-5/7)[d]	1.6-2.4	1.5-2.0
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	77 (3/14-4/7) 69 (4/8-23)[g]	56 (4/25-29) 43 (4/29-5/7)[d]	48	57
Inlet SO_2 Concentration, ppm	2,500-3,300	2,400-3,200	2,500-3,500	1,800-3,100
Percent SO_2 Removal	65-71	67-77	65-71	[illegible]
Scrubber Inlet pH Range	5.8-6.0	5.8-6.1	5.7-5.9	[illegible]
Scrubber Outlet pH Range (Weir/Downcomer)	5.4-5.7/ 5.4-5.7	5.4-5.7/ —	5.4-5.7/ 5.1-5.8	[illegible]
Percent Sulfur Oxidized	15-35	10-30	15-30	10-40
Solids Disposal System	Clarifier	Clarifier	Clarif. & centrifuge	Centrifuge[e]
Loop Closure, % Solids Disch.	20-29	19-25	57-60 (used venturi clarifier 5/16-17)	50-55 (25-29 from [illegible])
Clear Liquor to Mist Elim., gpm	10-22	13-23	41-55	20-30
Make-Up Water to Mist Elim., gpm	8-12	7-20	1-5	3-4
Dissolved Solids, ppm	6,900-8,900	3,700-5,000	11,000[c]	10,550[f]
Total ΔP Range, in. H_2O[b]	8.5-10.5	7.5-11.0	8.0-9.3	8.7-9.7
Mist Elim. ΔP Range, in. H_2O	0.17-0.25	0.16-0.35	0.15-0.22	0.15-0.17
Mist Eliminator Condition at End of Run	1/8" solids deposit bottom side.	1/4" slurry scale and some scale on top vanes of demister.	1/8" solids deposit on top side. Light, dust deposit on bottom side of mist elim.	50-60 mil scale on top vanes only.
Bed Condition at End of Run	40% of bed either plugged or marbles in stratified pattern.	60% of marbles stratified. 1 ft^2 area was plugged with solids.	25% of bed was plugged with solids and had stratified rows of marbles.	12% of bed plugged with solids. 60% of bed had stratified rows of marbles.
Inlet Duct Condition at End of Run	2 ft^3 of solids deposit between spray header and scrubber.	6 ft^3 of solids deposit blocking 60-70% of duct between header and scrubber.	1-1/2 ft^3 of solids deposit between header and scrubber.	1 ft^3 of solids deposit between header and scrubber.
Other Problems or Comments	Both soot blower airjets projecting forward. Several shutdowns due to plugged cooling and bottom spray nozzles. Swirl vanes in 13 of 16 CE bottom bed spray nozzles eroded away.	4 ST20FCN cooling spray nozzles replaced by ST24FCN nozzles at start of run. Swirl vanes in all 16 CE bottom bed nozzles disappeared. Swirl vanes in all 6 CE top bed nozzles lightly eroded.	2 cooling spray nozzles were found plugged. All CE bottom bed nozzles operated without swirl vanes. Swirl vanes in CE top bed nozzles still intact.	All 22 CE bed spray nozzles replaced by Spraco No. 1736 ramp bottom nozzles at start of run.

(a) Includes line-out.

(b) Total, excluding mist eliminator.

(c) Increasing steadily during run from 4,000 to 11,000 ppm, except for a brief decreasing period caused by use of venturi clarifier alone from 5/16 to 5/17.

(d) High stoichiometry range of 1.9 to 2.7 (43% average limestone utilization) caused by decreased limestone reactivity (i.e., larger average particle size).

(e) Used clarifier along from 8/10 - 8/11.

(f) Only one sample was taken during run.

(g) High stoichiometry range of 1.3 - 1.6 (69% average limestone utilization) caused by system degradation (i.e., erosion of slurry spray nozzles and marble bed pluggage).

Table 7-3 (continued)

SUMMARY OF LIMESTONE RELIABILITY VERIFICATION TESTS: MARBLE-BED SYSTEM

Run No.	506-3B	
Test Objectives	**Same as 505-3A with bed under spray nozzles raised higher.**	
Start-of-Run Date	6/15/73	
End-of-Run Date	7/2/73	
On Stream Hours[(a)]	380	
Gas Rate, acfm @ 330°F	20,000	
Gas Velocity, fps @ 125°F	5.5	
Liquor Rates to Top/Bottom Sprays, gpm	200/600	
L/G, gal/mcf	50	
Percent Solids Recirculated	9-11	
Effluent Residence Time, min.	30	
Stoichiometric Ratio, moles Ca/moles SO_2 absorbed	1.6-2.1	
Average % Limestone Utilization, 100x moles SO_2 absorbed/mole Ca	54	
Inlet SO_2 Concentration, ppm	2,100-3,200	
Percent SO_2 Removal	65-71	
Scrubber Inlet pH Range	5.5-5.8	
Scrubber Outlet pH Range (Weir/Downcomer)	5.5-5.6/ 5.0-5.2	
Percent Sulfur Oxidized	20-40	
Solids Disposal System	Centrifuge	
Loop Closure, % Solids Disch.	60-66	
Clear Liquor to Mist Elim., gpm	24-30	
Make-Up Water to Mist Elim., gpm	4-6	
Dissolved Solids, ppm	15,500-20,000	
Total ΔP Range, in. H_2O[(b)]	7.8-9.0	
MistElim. ΔP Range, in. H_2O	0.17-0.20[(c)]	
Mist Eliminator Condition at End of Run	**1/3 of the mist elim. (particularly SE corner) completely plugged.**	
Bed Condition at End of Run	**10% of bed plugged. 15% of marbles stratified.**	
Inlet Duct Condition at End of Run	**Extremely light solids accumulation at duct walls downstream of nozzles.**	
Other Problems or Comments	**One shutdown due to reheater pilot malfunction. One shutdown due to instrument air compressor valve leakage. Extended cooling spray nozzles to reach 2" from scrubber inlet.**	

(a) Includes line-out.

(b) Total, excluding mist eliminator.

(c) Range given is for period before 6/23. Increased steadily from 0.20 to 0.80 in. H_2O from 6/23 to 7/2.

Table 7-4

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: VENTURI/SPRAY TOWER SYSTEM

PARAMETER	TEST RUN							
	501-1A (645 Operating Hours)		502-1A (278 Operating Hours)		503-1A (256 Operating Hours)		506-1A (417 Operating Hours)	
	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run
Mist Eliminator Scaling or Plugging	Light scale on bottom vanes. Scattered scale on top vanes. Negligible solids deposits.	Fair	Moderate scale on top vanes. Scattered light solids deposits on bottom vanes at support box junctions.	Fair	No scale. Non-uniform, light, scattered solids deposits on bottom two rows of vanes.	Good	No scale. Moderate solids deposits around support I beams. About 10% of plastic top vanes damaged by solids dislodged from stack (Solids due to high entrainment of mist eliminator top flush).	Poor
Venturi and Spray Tower Mechanical Condition at End of Run	Slight erosion of guide vane bolts and surrounding area in venturi.	Fair	Moderate erosion of guide vanes, bolts and cross braces in venturi.	Fair	Slight erosion of guide vane cross braces in venturi.	Fair	Slight erosion in guide vane area of venturi. Slight erosion of top splash seal flange in venturi.	Fair
Venturi Scaling or Plugging	Scattered light scale on walls below plug. Moderate scale on walls of flooded elbow. Negligible solids deposits.	Good	Negligible scale on walls below plug. Moderate scale on walls of flooded elbow. Negligible solids deposits.	Good	Light scale on walls below plug. Moderate scale on walls of flooded elbow. Negligible solids deposits.	Good	Light scale on walls below plug and on walls of flooded elbow. Negligible solids deposits.	Good
Spray Tower Scaling or Plugging	Scattered light scale on walls. Scattered moderate solids deposits on top slurry header, on bottom mist eliminator wash header, and on bottom of trapout tray.	Good	Light scale on walls below trapout tray. Scattered light solids deposits on top slurry header, on bottom mist eliminator wash header, and on bottom of trapout tray.	Good	Light scale on walls below trapout tray. Light solids deposits on bottom of trapout tray.	Good	Light scale on all four spray headers and on about 50% of wall area above trapout tray. Light solids on bottom of trapout tray and adjacent walls.	Fair

Table 7-4 (continued)

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: VENTURI/SPRAY TOWER SYSTEM

PARAMETER	TEST RUN			
	507-1A (434 Operating Hours)		508-1A (28 Operating Hours)	
	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run
Mist Eliminator Scaling or Plugging	No scale. Negligible solids deposits on vanes. Scattered partial plugging of about 8% of top vane flow area.	Good	No scale. Negligible solids deposits. High entrainment of	Poor
Venturi and Spray Tower Mechanical Condition at End of Run	Slight erosion of guide vane assembly.	Fair	—	—
Venturi Scaling or Plugging	No scale. Moderate solids buildup at wet-dry interface due to discontinued soot blowing.	Good	—	—
Spray Tower Scaling or Plugging	Negligible scale and solids deposits.	Good	—	—

Table 7-5

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: TCA SYSTEM

PARAMETER	TEST RUN							
	501-2A (580 Operating Hours)		502-2A (553 Operating Hours)		508-2A (98 Operating Hours)		509-2A (465 Operating Hours)	
	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run
Mist Eliminator and Koch Tray Scaling or Plugging	Negligible scale and solids deposits.	Good	Light scale on vanes. About 15% of bottom vane flow area plugged by solids.	Poor	Negligible scale and solids deposits.	Good	Moderate scale on bottom two rows of vanes. Negligible solids deposits.	Good
Scrubber Mechanical[(a)] Condition at End of Run	Spheres from middle bed dropped to bottom bed through eroded grid wires.	Bad	Significant erosion of grid wires.	Bad	Loose, bent and eroded wires in two grids.	Bad	Broken and eroded wires in several grids.	Bad
Scrubber Scaling or Plugging	Negligible scale. Scattered solids deposits on walls below Koch tray.	Good	Negligible scale. Some solids deposits on slurry nozzles only.	Good	Negligible scale. Scattered moderate solids deposits on walls immediately below Koch tray.	Fair	Moderate scale on walls below bottom bed, light scale on walls of bottom two beds. Negligible solids deposits.	Fair
Inlet Duct Plugging	Slight solids buildup upstream and heavy solids buildup downstream of cooling sprays.	Bad	About 60% of duct area plugged immediately upstream of cooling sprays.	Bad	Moderate solids buildup upstream of cooling sprays.	Poor	Clean	Excellent

(a) No attempt was made to modify run conditions in order to solve the continuing problem of support grid erosion. The wire mesh grids (0.148 inch diameter wires) were replaced with sturdier 3/8 inch diameter rods (1 - 1/4 inch on center) prior to the long-term reliability test.

Table 7-5 (continued)

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: TCA SYSTEM

PARAMETER	TEST RUN					
	510-2A (297 Operating Hours)		514-2A (493 Operating Hours)		515-2A (571 Operating Hours)	
	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run	Comments	Relative Condition at End-of-Run
Mist Eliminator and Koch Tray Scaling or Plugging	Moderate scale on bottom vanes. About 25% of bottom vanes partially plugged with solids.	Fair	Flow area of bottom two vanes about 20% plugged with scale and solids (one quadrant about 50% plugged with hard crystalline solids.	Poor	Flow area of bottom two vanes about 40% plugged with scale and solids. Moderate solids buildup on underside of Koch tray, partially plugging several valves.	Bad
Scrubber Mechanical[a] Condition at End of Run	Loose and bent wires in several grids.	Bad	Loose, bent and broken wires in two middle grids.	Bad	Spheres from top bed dropped to middle bed through eroded grid wires.	Bad
Scrubber Scaling or Plugging	Scattered moderate to heavy scale on walls below bottom bed. Intermittent heavy scale on about 30% of bottom grid. Light scale on walls above bottom bed. Negligible solids deposits.	Poor	Light scale on bed walls. Heavy scale on 75% of bottom grid. Moderate scale and heavy solids on walls below Koch tray. Moderate scattered solids on walls below bottom bed.	Poor	Moderate scale between bottom bed and Koch tray. Heavy scale below bottom bed and on bottom grid. Intermittent heavy solids-scale deposits below bottom grid.	Bad
Inlet Duct Plugging	Clean	Excellent	Moderate solids buildup upstream of cooling sprays.	Fair	Clean	Excellent

[a] No attempt was made to modify run conditions in order to solve the continuing problem of support grid erosion. The wire mesh grids (0.148 inch diameter wires) were replaced with sturdier 3/8 inch diameter rods (1 - 1/4 inch on center) prior to the long-term reliability test.

Table 7-6

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: MARBLE-BED SYSTEM

PARAMETER	TEST RUN							
	501-3A & 3B (771 Operating Hours)		502-3A (285 Operating Hours)		503-3A & 3B (267 Operating Hours)		504-3A & 505-3A (233 Operating Hours)	
	Comment	Relative Condition at End-of-Run	Comment	Relative Condition at End-of-Run	Comment	Relative Condition at End-of-Run	Comment	Relative Condition at End-of-Run
Mist Eliminator Scaling or Plugging	Light scale on all vanes. Intermittent, moderate solids deposits on bottom vanes.	Fair	Moderate scale and solids deposits on top vanes. Light scale on bottom vanes.	Fair	No scale. Light solids deposits on top vanes.	Good	Moderate scale on top vanes. Light solids deposits on bottom vanes.	Fair
Scrubber Mechanical Condition at End of Run	Swirl vanes in 80% of bottom slurry nozzles completely eroded. Nozzle plugging by marbles dropped through loose grid.	Bad	All bottom slurry nozzles without swirl vanes.	Bad	About 20% of bottom slurry nozzles plugged with debris.	Bad	About 35% of bottom Spraco slurry nozzles partially plugged with marbles.	Poor
Scrubber Scaling or Plugging	Light scale on walls below bed. Intermittent heavy solids deposits on bottom spray headers & bottom of bed. About 30% of bed plugged or in stratified pattern.	Bad	Light scale on walls above and below bed and on all spray headers. About 2% of bed plugged, 60% stratified.	Poor	Light, intermittent scale-solids deposits on headers and walls above bed. Moderate scale-solids deposits on bottom headers. About 25% of bed plugged.	Bad	Moderate scale on walls above mist elim. and bed. Scattered, light scale-solids deposits on headers below bed. About 12% of bed plugged, 60% stratified.	Bad
Inlet Duct Plugging	About 25% of duct plugged downstream of cooling sprays.	Bad	About 70% of duct plugged immediately downstream of cooling sprays.	Bad	About 20% of duct plugged downstream of cooling sprays.	Poor	About 30% of duct plugged downstream of cooling sprays.	Bad

Table 7-6 (continued)

LIMESTONE RELIABILITY VERIFICATION TEST RUN EVALUATIONS: MARBLE-BED SYSTEM

PARAMETER	TEST RUN	
	506-3B (380 Operating Hours)	
	Comments	Relative Condition at End-of-Run
Mist Eliminator Scaling or Plugging	Light scale on bottom vanes. Moderate scale on top vanes. About 30% of middle vanes completely plugged, 30% partially plugged.	Bad
Scrubbing Mechanical Condition at End of Run	About 80% of bottom Spraco slurry nozzles severely eroded	Bad
Scrubber Scaling or Plugging	Moderate scale on walls throughout scrubber. Intermittent, heavy scale on all headers and walls below bottom headers. About 10% of bed plugged, 15% stratified.	Bad
Inlet Duct Plugging	About 45% of duct plugged downstream of cooling sprays. No solids downstream of open nozzle.	Bad

at an effluent residence time of 12 minutes, a percent solids recirculated of approximately 9 percent, a spray tower gas velocity of 8.0 ft/sec, and a liquid-to-gas ratio of 50 gal/mcf. Effluent residence times below 12 minutes could not be obtained during the testing due to system constraints.

During the venturi/spray tower runs, the underside (upstream) mist eliminator wash was effective in reducing the rate of soft solids accumulations on the lower mist eliminator blades at superficial velocities at or below 8 ft/sec (see Runs 503-1A and 507-1A), but topside plugging was a problem. A topside (downstream) wash was helpful in reducing plugging on the top blades, but there was evidence of droplet entrainment in the exiting flue gas with resultant accumulation of solids on the walls of the outlet duct (see Runs 506-1A, 507-1A, and 508-1A). More definitive information was gathered on mist eliminator operability during lime reliability testing (see Sections 9.2.2 and 10.2).

The polypropylene chevron mist eliminator (see Figure 3-4), used during Runs 502-1A through 506-1A, was discarded after it was damaged by solids falling onto it from the outlet duct.

7.1.2 TCA System

TCA reliability verification tests are reported in Table 7-2 and evaluated in Table 7-5. As expected, the relative system condition at the end of the initial TCA test 501-2A was good as far as scrubber or mist eliminator scaling and plugging was concerned. There was, however, difficulty experienced due to mechanical failure of a TCA support grid and plugging of the inlet duct at the hot-gas/liquid interface. During subsequent tests (see Runs 509-2A through 515-2A), the problem of inlet duct plugging was apparently solved, although there was still some accumulation of solids in the inlet duct during Run 514-2A (the resolution of the inlet duct plugging problem will be discussed in Section 10.4). The continual problem of erosion of TCA support grid wires was not solved during the remainder of the reliability verification tests. Sturdier support grids (parallel 3/8-inch rods) were installed in the TCA scrubber during subsequent long-term testing.

The results of the subsequent testing, under more economically attractive operating conditions, showed relatively good system condition after 465 on-stream hours with an effluent residence time of 20 minutes, a percent solids recirculated of approximately 9 percent, a gas velocity of 8.3 ft/sec, and a liquid-to-gas ratio of 75 gal/mcf (see Run 509-2A). A subsequent test at a gas velocity of 10.5 ft/sec and a liquid-to-gas ratio of 60 gal/mcf (Run 510-2A) gave some indication of scale buildup within the scrubber and partial plugging of the mist eliminator. Two final test runs at an effluent residence time of 4.4 minutes (Runs 514-2A and 515-2A) gave indications of severe scale buildup within the scrubber* and mist eliminator, and severe solids buildup in the mist eliminator and on the underside of the Koch tray. Effluent residence times between 4.4 and 20 minutes could not be obtained during these tests due to system constraints (the larger effluent hold tank was used for the 20 minute tests and a smaller recirculation tank for the 4.4 minute tests).

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*The maximum sulfate supersaturation within the scrubber system occurs at the scrubber effluent. Hence, scale formation is heaviest on the bottommost grid of the TCA.

The acceptable effluent residence time, therefore, is between 4.4 and 20 minutes at a recirculated solids concentration of approximately 9 percent (with 40 percent of solids as fly ash), a gas rate of approximately 8 ft/sec, and a liquid-to-gas ratio of approximately 75 gal/mcf. Tests at the EPA TCA pilot facility at Research Triangle Park have indicated that an effluent residence time of 10 minutes is satisfactory for a liquid-to-gas ratio equal to or greater than 65 gal/mcf and a percent solids recirculated of 10 percent.

7.1.3 Marble-Bed System

The condition of the Marble-Bed scrubber at the termination of the reliability verification tests was poor (see Tables 7-3 and 7-6). Problems associated with erosion of the Combustion Engineering slurry spray nozzles directed toward the underside of the Marble-Bed resulted in insufficient wetting and subsequent plugging of the bed. The use of hollow cone Spraco nozzles also caused insufficient wetting of the bed and subsequent plugging (see Runs 504-3A, 505-3A, and 506-3B).

7.2 ANALYTICAL DATA

A summary of scrubber inlet liquor analytical data for the limestone reliability verification tests is presented in Table 7-7. Except where noted, most of the dissolved species appear to have approached steady-state concentrations for these runs. The liquid analytical data are tested by inputting the measured compositions and pH's into the Bechtel Modified Radian Equilibrium Computer Program which then calculates the ionic imbalances and sulfate (gypsum) saturations. A listing of this

Table 7-7

AVERAGE SCRUBBER INLET LIQUOR COMPOSITIONS FOR LIMESTONE RELIABILITY VERIFICATION RUNS

Run No.	Percent Solids Recirculated	Effluent Residence Time, min.	Percent Solids Discharged	Percent Sulfur Oxidized	Scrubber Inlet pH Range	Inlet Liquor Species Concentrations, mg/l (ppm)									Calculated Percent Sulfate Saturation at 50°C[d]
						Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_3^{=}$	$SO_4^{=}$	$CO_3^{=}$	Cl^{-}	Total	
Venturi															
501-1A	15	20	20-28	5-25	5.8-6.0	2000	220	50	-	200	1300	200	3000	7000	96
506-1A	8	12	55-65	20-35	5.4-5.7	4200[a]	480[a]	140[a]	85[a]	200	2100	40	7800[a]	15,000[a]	167
507-1A[b]	8	12	53-68	25-45	5.3-5.7	5100	510	140	180	120	2400	25	10,200	18,800	204
TCA															
501-2A	15	20	25-48	20-40	5.7-6.0	1800	300	50	-	100	1600	100	2600	6500	109
502-2A	15	20	31-39	17-35	5.8-6.1	1600	200	100	40	150	1250	250	2200	5800	87
509-2A	8	20	26-45	32-60	5.5-5.8	2700	350	100	70	220	1900	250	4800	10,400	138
510-2A	8	20	26-44	35-55	5.4-5.6	3000	400	100	70	180	2000	80	5000	10,800	149
514-2A	15	4.4	27-52	20-50	5.2-5.6	3000	350	100	80	190	2000	70	5000	10,800	152
515-2A	8	4.4	34-44	25-50	5.2-5.4	3300	310	120	120	210	2500	20	5800	12,400	193
Marble-Bed															
501-3A & 3B	11	30	20-29	15-35	5.8-6.0	2200	200	50	-	250	1500	100	3500	7800	113
502-3A	11	30	19-25	10-30	5.8-6.1	1500	120	50	-	200	1000	200	2200	5300	74
505-3A[c]	11	30	60-65	10-30	5.6-5.8	2800	300	150	50	200	1400	250	5500	10,600	136
506-3B	11	30	60-66	20-40	5.5-5.8	5000	450	150	120	200	1800	250	9400	17,400	150

(a) Concentration at end of run. Concentration increasing throughout run.

(b) Concentrations for first half of run are listed. Percent solids discharged was 20-30% during second half (using clarifier only) and total dissolved solids decreased gradually to 11,300 ppm.

(c) Only one liquor analysis taken.

(d) Calculated Sulfate Saturation = (activity Ca^{++}) x (activity $SO_4^{=}$) / (solubility product at 50°C). A solubility product for $CaSO_4 \cdot 2H_2O$ of 2.2×10^{-5} was used (Radian Corporation, "A Theoretical Description of the Limestone-Injection Wet Scrubbing Process," NAPCA Report, June 9, 1970).

program is given in Appendix G. The original Radian program is described in Reference 9. For the data shown in Table 7-7, the calculated ionic imbalances were all less than 13 percent.

Venturi Runs 506-1A and 507-1A, and Marble-Bed Runs 503-3A through 506-3B demonstrate the higher degree of closed liquor loop operation that is achieved by use of the clarifier and centrifuge, rather than the clarifier alone, to separate solids (53 to 68 percent solids discharged vs. 19 to 29 percent). The increase in dissolved solids concentration at the higher percent solids discharge rates is due, primarily, to the increase in liquor chloride concentration.

7.3 SCALING POTENTIAL AS A FUNCTION OF LIQUOR SULFATE SATURATION

The calculated values for the degree of liquor saturation at 50°C with $CaSO_4 \cdot 2H_2O$ presented in Table 7-7 were made with the use of the Bechtel modified Radian program. The calculated degrees of sulfate saturations for the scrubber effluent liquors (which have not been presented in this report) are, of course, greater than the predicted saturations for the scrubber inlet liquors.

The major independent variables affecting the calculated sulfate saturations are: (1) percent solids recirculated, (2) effluent residence time, (3) scrubber inlet liquor pH, and (4) percent solids discharged. Oxidation of sulfite to sulfate, although not an independent variable, has a strong effect on sulfate saturation.

Generally, the calculated sulfate saturations decrease with increasing scrubber inlet liquor pH. Scrubber inlet liquor pH increases with an increase in percent solids recirculated and/or an increase in effluent residence time. Furthermore, the sulfate saturations tend to decrease with decreasing oxidation of sulfite to sulfate. Oxidation decreases with increasing liquor pH. In Figure 7-1, the calculated degree of scrubber inlet liquor sulfate saturation for all of the reliability verification tests is shown as a function of scrubber inlet liquor pH. In Figure 7-2, the calculated sulfate saturations for the TCA reliability verification tests are shown as a function of percent solids recirculated and effluent residence time.

The calculated sulfate saturations increase with increasing dissolved solids concentration, and, as discussed previously, the dissolved solids concentrations increase with increasing percent solids discharged. Hence, the "tighter" the closure of the liquor loop, the greater the potential for sulfate scaling.

As shown in Figure 7-2, the degree of sulfate saturation of the scrubber inlet liquor increased when effluent residence time decreased from 20 minutes to 4.4 minutes (Run 515-2A vs. 509-2A and 510-2A) and when the percent solids recirculated decreased from 16 to 8 percent at 4.4 minutes residence time (Run 515-2A vs. 514-2A). Sulfate scaling of the bottommost TCA grid occurred when the effluent residence time was decreased from 20 minutes to 4.4 minutes, and increased in severity when the percent solids was decreased from 16 to 8 percent at 4.4 minutes (see Table 7-2). From the data in Tables 7-2 and 7-7, it would appear that sulfate scaling is likely to occur in

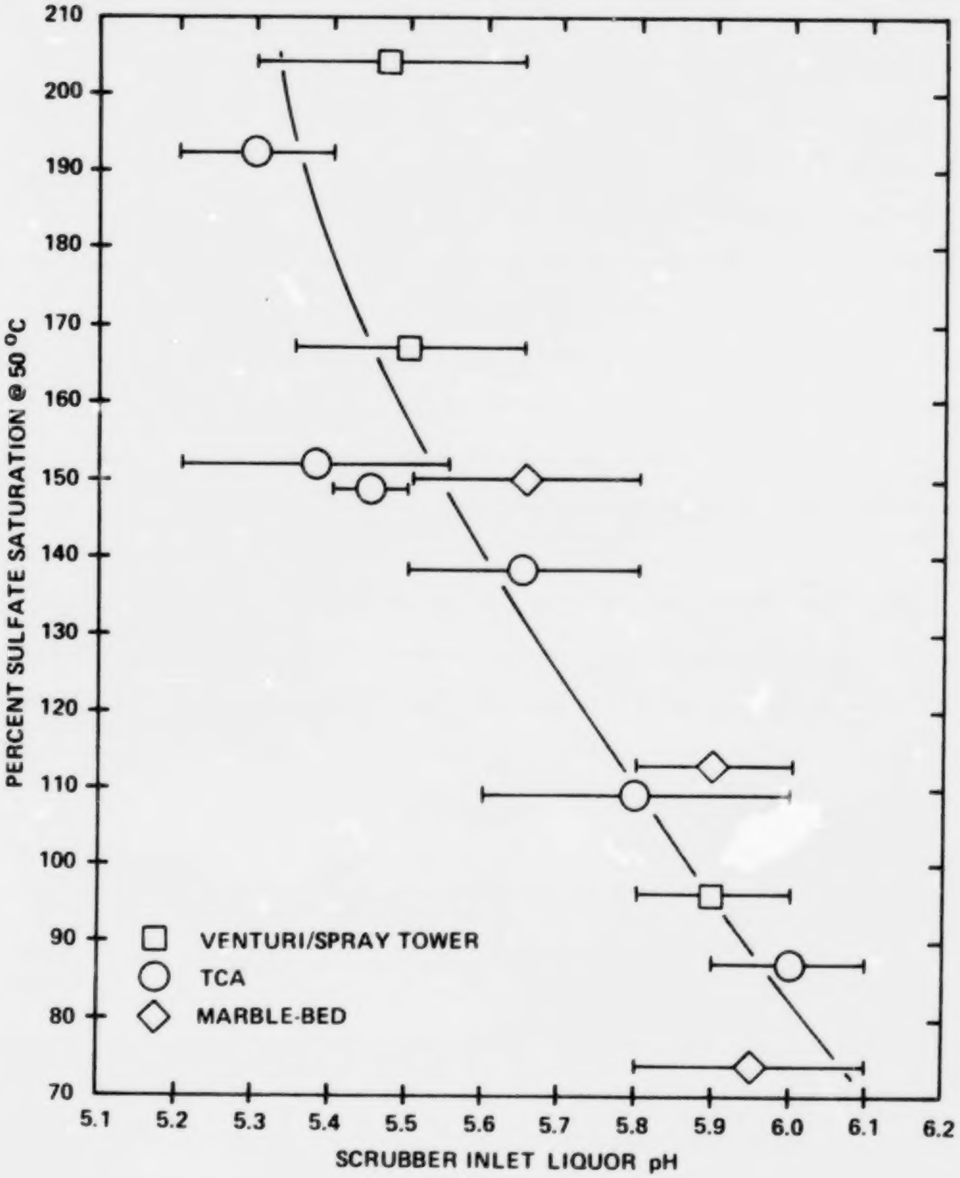

Figure 7-1. Calculated Degree of Sulfate Saturation versus pH for Limestone Reliability Verification Tests

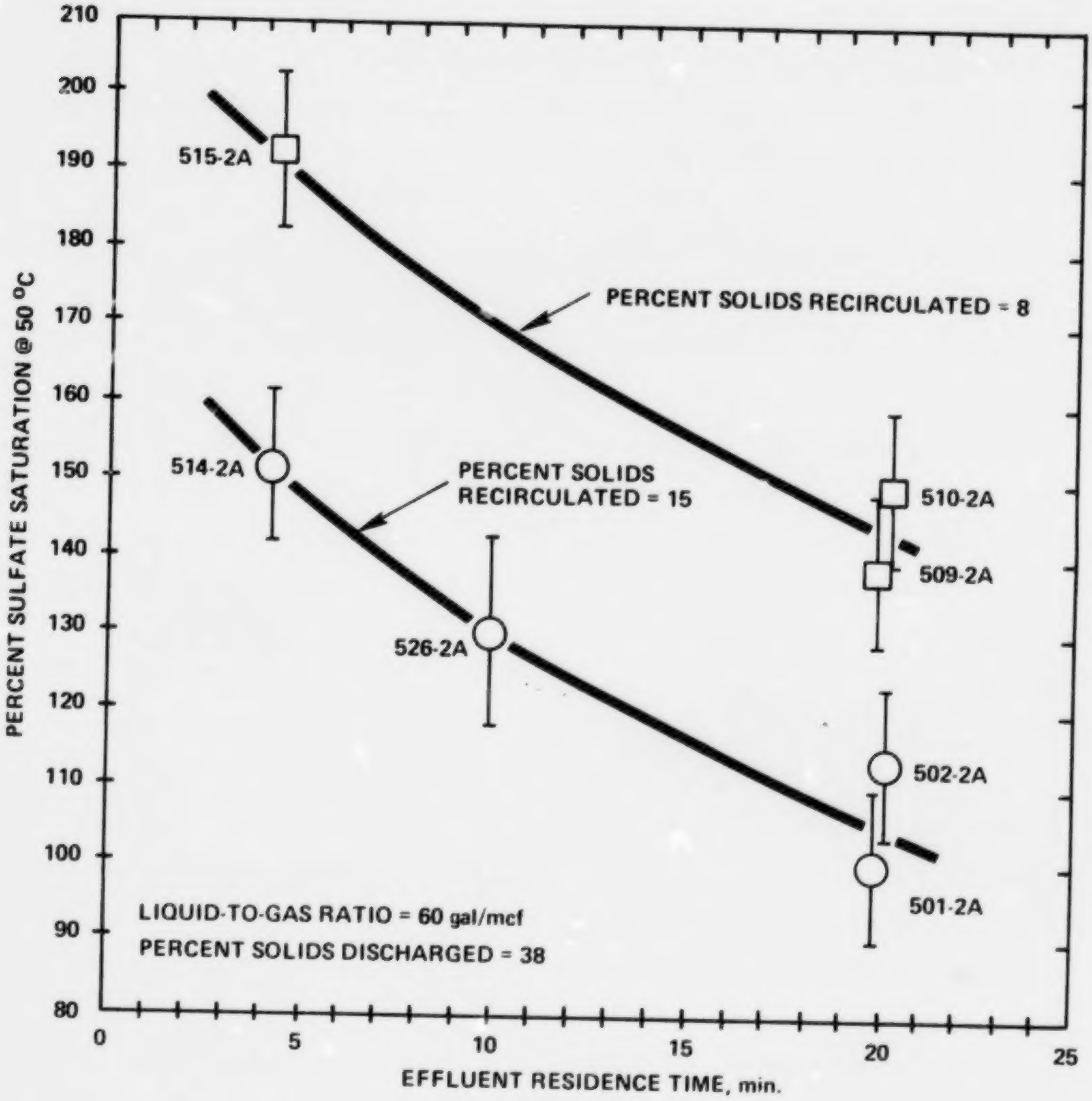

Figure 7-2. Calculated Degree of Sulfate Saturation for TCA Limestone Reliability Verification Tests

the TCA scrubber for a degree of sulfate saturation of the scrubber inlet liquor greater than approximately 135 percent. The Radian Corporation (Reference 10) has determined that the "critical" sulfate saturation at 45°C is approximately 130 percent.

A small amount of analytical data has been analyzed for the wash liquor to the spray tower and Marble-Bed mist eliminators and to the TCA Koch tray. The results showed that the inlet wash liquors, which are composed of mixtures of clarified process liquor and available raw water makeup, have approximately 60 percent of the degree of sulfate saturation of the scrubber inlet liquor at typical conditions. Even though the wash liquor may be less than saturated when introduced, SO_2 absorption and oxidation in the liquor on the mist eliminator surfaces can cause supersaturation and scaling.

7.4 LIMESTONE UTILIZATION

The results from the EPA TCA pilot facility at Research Triangle Park have shown that limestone utilization (100 x moles SO_2 absorbed/mole $CaCO_3$ added) is a strong function of limestone "reactivity" (i.e., average particle size) and scrubber inlet liquor pH (see Reference 11).

For the limestone reliability verification tests (see Tables 7-1, 7-2, and 7-3), average limestone utilizations for the venturi/spray tower, TCA, and Marble-Bed scrubbers were 68 percent, 77 percent, and 67 percent, respectively. Not included in the above averages were runs in which there was an apparent decrease in limestone reactivity (due to larger limestone average particle size) and in which the effect of "high pH" was being investigated (Runs 502-1A and 502-3A).

An example of a decrease in limestone utilization and increase in SO_2 removal due to an increase in inlet liquor pH can be seen by comparing TCA Run 501-2A and 502-2A (see Table 7-2). An increase in average scrubber inlet pH from 5.8 to 6.0 resulted in a decrease of utilization from approximately 80 to 60 percent and an increase in SO_2 removal from approximately 83 to 93 percent.

An example of changes in limestone reactivity (and, hence, in limestone utilization) due to changes in the average size of the limestone particles can be seen in Runs 501-1A (Table 7-1), 502-2A (Table 7-2), and 502-3A (Table 7-3).

7.5 MATERIAL BALANCES

The results of material balances for calcium and sulfur for many of the limestone reliability verification runs during continuous (uninterrupted) on-stream operating periods are given in Table 7-8. The SO_2 absorbed was computed from the measured inlet gas rate, the inlet and outlet gas SO_2 concentrations, and the estimated gas outlet rate. The calcium added was computed from the measured volumetric rate of limestone slurry additive and the solids concentration in the slurry. The sulfur and calcium discharged were computed from the measured rate of slurry discharged from the system and the concentrations of sulfur and calcium in the discharge.

The computed inlet and outlet rates for calcium and sulfur are in good agreement. The average stoichiometric ratios based on solids analyses are probably more accurate than the values based on limestone

Table 7-8

SUMMARY OF MATERIAL BALANCES FOR SULFUR AND CALCIUM FROM LIMESTONE RELIABILITY VERIFICATION TESTS

Run No.	Material Balance Period, hours	Sulfur Balance			Calcium Balance			Average Stoichiometric Ratio, Moles Ca Added/Mole SO_2 Absorbed	
		SO_2 Absorbed, lb-moles/hr	SO_x in Solids Discharged, lb-moles/hr	Percent Error	Ca in Limestone Feed, lb-moles/hr	Ca in Solids Discharged, lb-moles/hr	Percent Error	Based on Limestone Added and SO_2 Absorbed	Based on Solids Analysis
Venturi									
501-1A	605	4.3	4.5	+4	7.1	7.8	+9	1.67	1.73
502-1A	210	3.9	4.0	+2	6.2	7.4	+16	1.59	1.82
TCA									
501-2A	150	4.7	4.3	-9	4.5	5.0	+10	0.95	1.15
502-2A	170	5.6	6.0	+7	11.6	10.6	-9	2.07	1.77
509-2A	465	4.7	4.1	-15	4.9	5.7	+14	1.03	1.38
M-B									
501-3A	150	4.2	4.1	-2	4.5	5.2	+13	1.06	1.26
501-3B(a)	140	4.3	4.4	+2	6.2	6.2	0	1.45	1.42
506-3B(b)	360	3.8	4.2	+10	6.8	7.4	+8	1.78	1.77

(a) Because of turbid clarifier overflow, some of the solids in the clarifier feed is returned to the scrubber. The values for SO_x and Ca discharged have been corrected for solids returned and are net discharge from the system.

(b) The values for SO_x and Ca discharged have been corrected for solids in the centrate returned to the scrubber.

addition rate and SO_2 absorption, due to uncertainties in the measurement of limestone slurry feed rate. The ionic imbalances for the bleed stream solids analyses, from which the calcium and sulfur discharge rates were calculated, averaged less than +5 percent (more cations than anions).

The continuous operating periods shown in Table 7-8 were broken up into "computational periods" of from 8 to 48 hours, material balances were made for each computational period, and the results were summed. The computed inlet and outlet rates for calcium and sulfur did not necessarily balance during each computational period, due to the unsteady conditions which prevail at any point in time (i.e., changing percent solids) and the resultant accumulation (or depletion) of the species within the system. However, over a longer period of time ($>$ 150 hours) the accumulation term becomes negligible as compared to the total input or output of species.

Section 8

LIMESTONE RELIABILITY TEST RESULTS

Performance and analytical data from the TCA system limestone reliability testing at the Shawnee test facility are presented in this section, along with an evaluation of each reliability test and the conclusions drawn, to date, from the testing.

8.1 PERFORMANCE DATA AND TEST EVALUATION

A summary of the test conditions and results for each of the TCA limestone reliability tests is presented in Table 8-1, along with the run philosophies. A summary of the scrubber inlet liquor analytical data for a majority of the tests is presented in Table 8-2, along with the calculated percent sulfate saturations. Properties of coal and limestone used during these tests can be found in Appendix C. Essential operating data for most of the TCA limestone reliability tests are graphically presented in Appendix H. An evaluation and discussion of each test is presented in the following sections.

8.1.1 TCA Run 525-2A

On October 24, 1973, the initial limestone long-term reliability test (Run 525-2A) was begun on the TCA system. The objective of the test

Table 8-1

SUMMARY OF LIMESTONE RELIABILITY TESTS ON TCA SYSTEM

Run No.	525-2A	526-2A	527-2A	528-2A
Start-of-Run Date	10/24/73	11/21/73	1/18/74	2/6/74
End-of-Run Date	11/15/73	1/15/74	1/24/74	2/26/74
On Stream Hours	517	1190	133	425
Gas Rate, acfm @ 300°F	25,000	20,500	20,500	20,500
Gas Velocity, fps @ 125°F	10.5	8.6	8.6	8.6
Liquor Rate, gpm	1200	1200	1200	1200
L/G, gal/mcf	60	73	73	73
Percent Solids Recirculated	14-16	14-15.5	15-16	14-16
Effluent Residence Time, min.	10	10	10	12
Stoichiometric Ratio, moles Ca added/mole SO_2 absorbed	1.2-1.6	1.2-1.7	1.5-1.9	1.1-1.45
Avg % Limestone Utilization, 100x moles SO_2 abs./mole Ca added	71	69	59	78
Inlet SO_2 Concentration, ppm	1800-4000	1600-4300	2600-3800	2000-4000
Percent SO_2 Removal	73-88	75-87	75-85	79-90
Scrubber Inlet pH Range	5.5-6.1	5.45-5.9	5.75-5.9	5.7-5.95
Scrubber Outlet pH Range	5.2-5.8	5.1-5.4	5.3-5.5	5.2-5.6
Percent Sulfur Oxidized	15-30	15-35	15-35	10-30
Solids Disposal System	Clarifier	Clarifier	Clarifier	Clarifier
Loop Closure, % Solids Dischg.	31-42	35-47	34-39	25-33
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	140	130	130	110
Total Dissolved Solids, ppm	7000-9600	7600-9700	7700-8900	4200-6800
Total ΔP Range Excluding Mist Eliminator and Koch Tray, in. H_2O	5.5-6.5	4.3-4.7	4.5-4.9	4.9-5.3
Mist Eliminator and Koch Tray ΔP Range, in. H_2O	2.3-2.7 (10/24-11/12) 2.7-3.1 (11/12-11/15)	1.9-2.1	2.1-3.1	2.0-2.2
Mist Eliminator ΔP Range, in. H_2O	--	0.15-0.26	0.30-2.00	0.16-0.20
Absorbent	Limestone slurried to 60 wt % with makeup water and added to EHT.	Limestone slurried to 60 wt % with makeup water and added to EHT.	Limestone slurried to 60 wt % with makeup water and added to EHT.	Limestone slurried to 60 wt % with makeup water and added to EHT.
Mist Eliminator/Koch Tray	No mist eliminator wash. K. T. (2" weir height) irrigated with available makeup water (~3 gpm) and all available clarified liquor (~15 gpm). Bottom of Koch tray steam sparged 1 min/hr.	No mist eliminator wash. K. T. (2" weir height) irrigated with available makeup water (~8 gpm) and all available clarified liquor (~15 gpm). Bottom of Koch tray steam sparged 1 min/hr.	No mist eliminator wash. K. T. (3" weir height) irrigated with available makeup water (~7 gpm) and all available clarified liquor (~15 gpm). Was not irrigated for 2 hr period. Bottom of Koch tray steam sparged 1 min/hr.	No mist eliminator wash. K. T. (2" weir height) irrigated open-loop (once-through) with 25 gpm raw water only. Bottom of Koch tray steam sparged 1 min/hr.
Scrubber Internals	3 stages (4 grids) with 5" spheres/stage. Top bed-new TPR spheres. Middle & bottom-new HDPE spheres.	3 stages (4 grids) with 5" spheres/stage. Top bed-new HDPE spheres. Middle & bottom-worn HDPE's from previous run.	2 stages (3 grids) with 7 1/2" spheres/stage. Top bed-5" worn + 2 1/2" new HDPE spheres. Bottom bed-new HDPE's. Slurry nozzles not used (open pipe only) for this run only.	3 stages (4 grids) with 5" spheres/stage. All beds-new TPR spheres.
System Changes Before Start of Run	System (scrubber, Koch tray, and mist eliminator) cleaned.	System cleaned. Replaced top bed spheres with new HDPE spheres. EHT outlet (Koch tray inlet) pump switched from centrifugal to hydroseal.	System not cleaned. Removed top grid and bed of spheres. Middle bed-5" HDPE spheres from top bed + 2 1/2" new HDPE's. Bottom bed-7 1/2" new HDPE's. Removed inlet slurry nozzles. Increased Koch tray weir height to 3".	System cleaned. Returned to 3 stages (4 grids) with 5" new TPR spheres/stage. Reinstalled inlet slurry nozzles. Installed Elliot strainer on scrubber loop. Decreased Koch tray weir height to 2".
Method of Control	SO_2 removal controlled at 84±2%	SO_2 removal controlled at 84±2%	SO_2 removal controlled at 84±2%	SO_2 removal controlled at 84±2% Overrides: Inlet pH ≤ 5.95 Stoich. Ratio ≤ 1.45
Run Philosophy	Intended long-term. Conditions chosen for long-term reliability based on reliability verification tests.	Intended long-term. Velocity reduced for reliability. HDPE spheres to be used until strainers are installed on scrubber loop.	Intended short-term. To determine whether changes in scrubber internal configuration could reduce slurry solids carryover.	Intended 2 wks. To observe any effect on mist eliminator solids and scale deposits with raw water only for Koch tray irrigation.
Results	Terminated due to rapidly increasing pressure drop across mist elim. and Koch tray. Large solids deposits on underside of Koch tray and on scrubber walls between tray and main slurry header. TPR ball-spheres plugged inlet slurry nozzles (believed to be primary problem). Scrubber stages scale-free. Bottom of mist eliminator 58% plugged.	Terminated to replace worn HDPE spheres with new HDPE spheres. Some solids accumulation between slurry nozzles and Koch tray (due to partial pluggage of spray nozzles with foreign materials). Bottom of mist eliminator 14% plugged.	Inconclusive. Solids carryover to Koch tray and mist eliminator appeared equal to or greater than previous run. Bottom of mist eliminator 15% plugged.	Mist eliminator and Koch tray areas clean. Due to less tight liquor loop from seepage of Koch tray raw water, calculated sulfate saturation was slightly lower at 110%.

Table 8-1 (continued)

SUMMARY OF LIMESTONE RELIABILITY TESTS ON TCA SYSTEM

Run No.	529-2A	530-2A	531-2A	532-2A
Start-of-Run Date	2/26/74	3/28/74	5/10/74	7/17/74
End-of-Run Date	3/7/74	4/17/74	6/26/74	7/29/74
On Stream Hours	213	476	1088	288
Gas Rate, acfm @ 300°F	20,500	20,500	20,500	20,500
Gas Velocity, fps @ 125°F	8.6	8.6	8.6	8.6
Liquor Rate, gpm	1200	1200	1200	1700
L/G, gal/mcf	73	73	73	104
Percent Solids Recirculated	14.5-16	14-16	7-9	7-9
Effluent Residence Time, min.	12	12	12	12
Stoichiometric Ratio, moles Ca added/mole SO_2 absorbed	1.15-1.35	1.2-1.55	1.3-1.7 (5/10-26, 6/19-26) 1.0-1.2[a] (5/26-6/19)	0.88-1.28[b]
Avg % Limestone Utilization, 100x moles SO_2 abs./mole Ca added	80	73	67 (5/10-26, 6/19-26) 91[a] (5/26-6/19)	91[b]
Inlet SO_2 Concentration, ppm	2300-3900	2200-4200	1750-3750	2000-3900
Percent SO_2 Removal	79-89	78-89	71-96	96-99
Scrubber Inlet pH Range	5.7-5.9	5.75-5.95	5.4-6.1	5.6-6.0
Scrubber Outlet pH Range	5.2-5.5	5.1-5.4	4.7-5.5	5.2-5.6
Percent Sulfur Oxidized	15-30	12-29	13-40	7-25
Solids Disposal System	Clarifier	Clarifier (Centrifuge only after 4/10)	Clarifier	Clarifier
Loop Closure, % Solids Dischg.	30-47	30-43	[illegible]-42	32-43
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	130	120	100	140
Total Dissolved Solids, ppm	8400	6300-8600	25,000	45,000-60,000
Total ΔP Range Excluding Mist Eliminator and Koch Tray, in. H_2O	4.9-5.3	4.8-5.1	4.3-6.6	4.5-4.8
Mist Eliminator and Koch Tray ΔP Range, in. H_2O	1.9-2.1	1.9-2.1	2.1-3.7	1.95-2.1
Mist Eliminator ΔP Range, in. H_2O	0.19-0.23	0.17-0.25	0.19-0.36	0.15-0.19
Absorbent	Limestone slurried to 60 wt % with makeup water and added to EHT.	Limestone slurried to 60 wt % with clarified process liquor and added to EHT.	Limestone slurried to 60 wt % with clarified process liquor and added to EHT.	Limestone slurried to 60 wt% with clarified process liquor and added to EHT.
Mist Eliminator/Koch Tray	No mist eliminator wash. K. T. (2" weir height) irrigated with available makeup water (~5 gpm) and all available clarified liquor (~15 gpm). Bottom of Koch tray steam sparged 1 min/hr.	No mist eliminator wash. K. T. (2" weir height) irrigated with 8 gpm makeup water and 7 gpm clarified liquor. Bottom of Koch tray steam sparged 1 min/hr.	No mist eliminator wash. K. T. (3" weir height) irrigated with available makeup water (~9 gpm) and all available clarified liquor (~30 gpm). Bottom of Koch tray steam sparged 1 min/hr.	Recycle loop around mist eliminator/K. T. Bottom of mist elim. washed with 8 gpm makeup water plus 7 gpm recycle liquor. K. T. (2" weir ht.) irrigated with ~35 gpm recycle liquor (plus 15 gpm mist elim. wash). Bottom of K. T. steam sparged 1 min/hr.
Scrubber Internals	3 beds (4 grids) with 5" spheres/bed. All beds-worn TPR spheres from previous run.	3 beds (4 grids) with 5" spheres/bed. All beds-worn TPR spheres from previous run.	3 beds (4 grids) with 5" spheres/bed. All beds-worn TPR spheres from previous run.	3 beds (4 grids) with 5" spheres/bed. All beds-worn TPR spheres from previous run.
System Changes Before Start-of-Run	No cleaning. No changes.	System cleaned. Koch tray periphery sealed. PWHT outlet (Koch tray inlet) pump converted from Hydroseal to Centriseal. Provided clarified liquor for limestone slurry feed tank. Modified piping to obtain constant Koch tray makeup water/liquor ratio. Sealed top of EHT.	System cleaned. Installed MgO add'n system. Lowered spray header 4". Leveled Koch tray and further sealed periphery. Increased weir height to 3". Installed inlet weir. EHT overflow line blanked.	System cleaned. Provided for closed-circuit recycle loop around mist eliminator/Koch tray, including mist eliminator underwash. Lowered weir height to 2". EHT and PWHT sealed with CO_2 gas purge.
Method of Control	SO_2 removal controlled at: 84±2% Overrides: Inlet pH ≤ 5.95 Stoich. Ratio ≤ 1.65	SO_2 removal controlled at 84±2% Overrides: Inlet pH ≤ 5.95 Stoich. Ratio ≤ 1.65	SO_2 removal controlled at: 5/10-5/23 84±2% 5/23-6/5 78±2% 6/5-6/19 84±2% 6/19-6/26 95±2%	Scrubber inlet pH controlled at 5.8±0.2
Run Philosophy	Intended long-term. Test conditions same as previous run, except Koch tray irrigated with all available makeup water and clarified liquor.	Intended long-term. EHT sealed to reduce oxidation, and Koch tray wash ratio held constant to observe any effect on solids buildup.	Intended long-term. Attempt to operate unsaturated with MgO add'n to sealed EHT. Percent solids lowered to 8% to provide additional clarifier liquor for Koch irrigation.	Intended long-term. Attempt to operate unsat. with MgO add'n to EHT (10,000 ppm Mg). 1700 gpm liquor rate, EHT & PWHT CO_2 blanket, mist elim. wash & mist elim/Koch tray recycle loop.
Results	Routine inspection after 213 hours revealed some soft solids and slight scale buildup on the mist elim. lower vanes. Although amount of scale and solids was slight, it was considered to be significant after only 213 hours, and run was terminated. Bottom of mist eliminator 19% plugged.	Unable to significantly reduce oxidation or sulfate saturation. Run terminated due to heavy scale and solids deposits on top of Koch tray, possibly caused by low (15 gpm) Koch tray flush rate and a clarifier rake malfunction on April 8 - 10, resulting in abnormal solids carry-over to Koch tray. Bottom of mist eliminator 44% plugged.	Unable to maintain unsaturated sulfate operation with 5000 ppm Mg. Steady state operation was not reached. Run terminated due to solids and scale buildup on mist eliminator, Koch tray and bottom grid. Bottom of mist eliminator 15% plugged. [a] Total stoich. ratio for Ca & Mg is 1.08-1.28 (avg. alkali util. 85%).	Unable to attain unsaturated sulfate operation with 10,000 ppm Mg. Run terminated due to scale build-up on Koch tray and loss of 4000 (~1/2 bed) spheres through grids. Bottom of mist eliminator 1-2% plugged. [b] Total stoich. ratio for Ca & Mg is 1.05-1.45 (avg. alkali util. is 80%).

Table 8-1 (continued)

SUMMARY OF LIMESTONE RELIABILITY TESTS ON TCA SYSTEM

Run No.	533-2A	534-2A	535-2A	
Start-of-Run Date	8/6/74	9/3/74	9/12/74	
End-of-Run Date	8/21/74	9/8/74	In Progress	
On Stream Hours	332	100	948 (as of 10/22/74)	
Gas Rate, acfm @ 300°F	20,600	20,600	20,600	
Gas Velocity, fps @ 125°F	8.6	8.6	8.6	
Liquor Rate, gpm	1200	1200	1200	
L/G, gal/mcf	73	73	73	
Percent Solids Recirculated	14.5-15.5	10-12.5	12-16	
Effluent Residence Time, min.	12	12	12(9/12-9/27), 15(after 9/27)	
Stoichiometric Ratio, moles Ca added/mole SO$_2$ absorbed	0.86-1.31[a]	1.10-1.30	1.35-1.70	
Avg % Limestone Utilization, 100x moles SO$_2$ abs./mole Ca added	92[a]	82	65	
Inlet SO$_2$ Concentration, ppm	2000-3750	2700-3600	2000-4000	
Percent SO$_2$ Removal	95-99	75-90	77-88	
Scrubber Inlet pH Range	5.7-6.0	5.65-5.85	5.7-6.0	
Scrubber Outlet pH Range	5.3-5.65	5.2-5.4	5.1-5.6	
Percent Sulfur Oxidized	15-21	15-30	15-35	
Solids Disposal System	Clarifier	Clarifier	Clarifier	
Loop Closure, % Solids Dischg.	29-38	8-40	36-42	
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	135	130	120 (after 9/27)	
Total Dissolved Solids, ppm	33,000-48,000	7900-9100	6000-8000	
Total ΔP Range Excluding Mist Eliminator and Koch Tray, in.H$_2$O	4.10-4.95	4.30-4.55	4.00-4.60	
Mist Eliminator and Koch Tray ΔP Range, in. H$_2$O	2.30-3.45	1.85-2.00	1.30-2.05	
Mist Eliminator ΔP Range, in. H$_2$O	0.17-0.24	0.15-0.20	0.10-0.20	
Absorbent	Limestone slurried to 10 wt% with clarified process liquor and added to EHT.	Limestone slurried to 10 wt% with clarified process liquor and added to EHT.	Limestone slurried to 10 wt% with clarified process liquor and added to EHT.	
Mist Eliminator/Koch Tray	Recycle loop around mist eliminator/K.T. Bottom of mist elim. washed with 8 gpm makeup water plus 7 gpm recycle liquor. K.T. (2" weir ht.) irrigated with 35 gpm recycle liquor (plus 15 gpm mist elim. wash). Bottom of K.T. steam sparged 1 min/hr.	Bottom of mist elim. washed cont. with 15 gpm dil. clar. liq. (~8 gpm makeup water + ~7 gpm clar. liq.). K.T. (2" weir ht.) irrig. with ~8 gpm clar. liq. + 15 gpm mist elim. wash. Bottom of Koch tray steam sparged 1 min/hr.	Bottom of mist elim. washed cont. with 15 gpm dil. clar. liq. (~9 gpm makeup water + ~6 gpm clar. liq.). K.T. irrig. with ~9 gpm clar. liq. + 15 gpm mist elim. wash. Total clar. liq. to mist elim. & K.T. 15 gpm min. Bottom of Koch tray steam sparged 1 min/hr.	
Scrubber Internals	3 stages (4 grids) with 5 inches spheres/stage. All beds-new TPR sphere.	3 stages (4 grids) with 5 inches spheres/stage. All beds-worn TPR spheres from previous run.	3 stages (4 grids) with 5 inches spheres/stage. All beds-worn TPR spheres from previous run.	
System Changes Before Start-of-Run	System cleaned. Replaced worn TPR spheres with new TPR's.	System cleaned.	System cleaned. Seal water removed from cooling spray pump.	
Method of Control	Scrubber inlet pH controlled at 5.8±0.2	Scrubber inlet pH controlled at 5.8±0.1	SO$_2$ removal controlled at 85±2%. Overrides: Inlet pH ≤ 6.0 Stoich. Ratio ≤ 1.[illegible]	
Run Philosophy	Intended long-term. Attempt to operate unsat. with 10,000 ppm Mg conc. in EHT. 1200 gpm liquor rate, 15% solids, [illegible] blanket over EHT & [illegible], and mist elim./KT recycle loop.	Intended long-term. Discontinue use of MgO. Test conditions chosen similar to 526-2A.	Intended long-term. Test conditions chosen similar to 526-2A.	
Results	Unable to attain unsaturated sulfate operation with 10,000 ppm Mg. Run terminated due to scale build up on Koch tray and mist eliminator. Bottom of mist eliminator 12% plugged. (a) Total stoich. ratio for Ca & Mg is 1.01-1.48 (Avg. alkali util. 80%).	Run terminated due to scale buildup on the Koch tray. Bottom of mist eliminator 1-2% plugged.	Inspection of system at 780 hrs showed mist elim. and Koch tray to be essentially clean. Heavy solids buildup on walls between steam sparger and slurry spray header. 30 mils scale on all grids.	

Table 8-2

AVERAGE SCRUBBER INLET LIQUOR COMPOSITIONS AND CALCULATED SULFATE SATURATIONS FOR TCA LIMESTONE RELIABILITY RUNS

Run No.	Percent Solids Recirculated	Effluent Residence Time, min.	Percent Solids Discharged	Percent Sulfur Oxidized	Scrubber Inlet pH Range	Inlet Liquor Species Concentrations, mg/l (ppm)									Calculated Percent Sulfate Saturation at 50°C[(d)]
						Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_3^{=}$	$SO_4^{=}$	$CO_3^{=}$	Cl^{-}	Total	
525-2A	14-16	10	31-42	15-30	5.5-6.1	2100	250	80	50	80	2000	70	3200	7900	140
526-2A	14-15.5	10	35-47	15-35	5.65-5.9	2300	340	60	140	80	1900	210	3700	8700	130
528-2A	14-16	12	25-33	10-30	5.7-5.95	1400	200	30	120	150	1600	260	1600	5400	110
529-2A[(a)]	14.5-16	12	30-47	15-30	5.7-5.9	1900	330	120	520	30	2000	180	3300	8400	130
530-2A[(b)]	14-16	12	30-43	12-25	5.75-5.95	1730	340	50	120	120	1900	320	2790	7370	120
532-2A	7-9	12	32-43	7-25	5.6-6.0	570	10,500	60	110	3000	38,700	30	2400	56,900	145
533-2A	14.5-15.5	12	29-38	15-23	5.7-6.0	715	11,800	60	110	2570	37,200	200	3100	55,750	135
534-2A	10-12.5	12	30-40	15-30	5.65-5.85	2220	170	40	180	70	1730	90	3540	8040	130
535-2A[(c)]	11.5-15.5	15	35-42	15-25	5.8-6.0	1850	290	50	70	60	1800	80	3060	7260	120

Note: Average concentrations are for steady-state operating periods. Solids disposal system: Clarifier only.

(a) Only one sample was taken during steady-state operation.

(b) Solids disposal systems: Clarifier only for first two-thirds of test, then centrifuge only.

(c) Test run was started on 9/12/74 with 12 minutes residence time. Residence time was increased to 15 minutes on 9/27. The run is still in progress as of 10/16. The values given in the table are for period 9/27 through 10/16.

(d) Calculated Sulfate Saturation = (activity Ca^{++}) x (activity $SO_4^{=}$)/(solubility product at 50°C). A solubility product for $CaSO_4 \cdot 2H_2O$ of 2.2×10^{-5} was used (Radian Corporation, "A Theoretical Description of the Limestone-Injection Wet Scrubbing Process," NAPCA Report, June 9, 1970).

was to operate continuously for from four to six months. The operating conditions selected for the run were based on the results of the reliability verification tests (see Figure 7-2) and the tests conducted at the EPA pilot facility at Research Triangle Park . The major test conditions were (see Table 8-1):

Gas Velocity	10.5 ft/sec
Liquid-to-Gas Ratio	60 gal/mcf
Percent Solids Recirculated	15
Effluent Residence Time	10 min.
Percent SO_2 Removal (controlled)	84

During this test, the Koch Flexitray was irrigated with the available raw water makeup plus all the clarified liquor at an approximately one to two ratio, and the effluent irrigation liquor was routed to the scrubber effluent hold tank. The mist eliminator, at that time, had no provision for independent underside wash and was washed only with liquid entrainment from the Koch tray.

For the first time, thermoplastic rubber (TPR) spheres, purchased from UCP, were tested in the scrubber. They were used in the top bed while the bottom two beds were charged with high density polyethylene (HDPE) spheres, also purchased from UCP. The original wire mesh grids (which eroded during the limestone reliability verification runs) had been replaced by sturdier bar-grids for the long-term reliability runs.

After 517 hours of operation the run was terminated due to unusually heavy solids buildup on the underside of the Koch Flexitray and scale and solids buildup on the bottom vanes of the mist eliminator (about 60 percent of the free area was plugged). Numerous (over 200) half-spheres of the TPR type were found in the scrubber and slurry circulating system. TPR half-spheres were also found lodged in two of the four inlet slurry spray nozzles. It should be noted that the scrubber beds (and bottommost grid) were essentially free of scale after the 517 hour operating period. The calculated scrubber inlet liquor sulfate saturation of 140 percent (see Table 8-2) was only slightly higher than the 135 percent estimated from the limestone reliability verification tests to be required for scale-free operation.

It is hypothesized that the accumulation of soft solids below the Koch tray was due, primarily, to the partial blockage of the slurry inlet nozzles, resulting in excessive entrainment of the fine slurry droplets. This excessive entrainment and the high gas velocity (10.5 ft/sec) most probably contributed to the mist eliminator pluggage.

8.1.2 TCA Run 526-2A

Run 526-2A was begun on November 21, 1973. The TPR spheres in the top bed had been replaced with HDPE spheres*, and the accumulated scale and soft solids from Run 525-2A had been removed. The run conditions were identical to those for Run 525-2A, except that the gas velocity was reduced to 8.6 ft/sec. The velocity was reduced because more detailed investigation of previous reliability verification runs (see Section 7) indicated that long-term reliability for the present Koch tray/mist eliminator configuration could not be expected at a gas velocity of 10.5 ft/sec.

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*It was planned to use TPR spheresin all three stages following the installation of strainers in the inlet slurry piping.

On January 10, 1974, the run was interrupted after 1190 hours of on-stream operation to check the wear of the HDPE spheres in the three beds (HDPE sphere life had been estimated to be less the 2000 hours). The average percent weight loss for the HDPE spheres in the bottom two beds was found to be approximately 32 percent for 1707 hours of use (Runs 525-2A and 526-2A).

Pressure drop across the chevron mist eliminator had increased slightly during the initial 800 hours of operation, and during the last 400 hours, increased more rapidly to a final level about 1.5 times the initial value of 0.18 inch H_2O.

The general appearance of the system was good. Scattered solids deposits (up to 1 inch) and light scale (about 1/16 inch) was found on the scrubber walls below the bottommost grid and on the wall areas not in contact with the spheres. The four bar-grids were covered with 10 to 14 mil scale on the inactive surfaces (i.e., surfaces not in contact with spheres).

A heavy, relatively uniform solids layer covered the underside of the wash tray. All four inlet slurry spray nozzles were partially plugged with debris, primarily with plastic covering from pipe insulation. The flange of the steam sparger underneath the wash tray was found to be leaking. Mist eliminator plugging was confined to the bottom two passes only, reducing the free flow area by about 15 percent. Several small pieces of solids fell from the outlet gas duct and rested on top of the center section of the mist eliminator. The area restricted by these pieces was insufficient to affect the pressure drop across the mist eliminator.

As with Run 525-2A, it is hypothesized that the solids accumulations on the slurry inlet spray nozzles and header, on the adjacent scrubber walls, and on the underside of the Koch wash tray were primarily caused by partial blockage of the TCA slurry inlet spray nozzles by debris, which changed the spray pattern and caused excessive entrainment of fine slurry droplets. Also, the blocked nozzles may have been a major factor contributing to the mist eliminator pluggage observed. It should be noted that the accumulation of sulfate scale on the bottommost bar-grid (10 to 14 mils) was not excessive after the approximately 1200 hours of operation. This was to be expected, since the scrubber inlet slurry was only 130 percent saturated with respect to calcium sulfate (see Table 8-2).

After inspection of the scrubber, it was decided not to restart Run 526-2A, but to conduct a short-term test with certain changes in the scrubber internal configurations before attempting a new long-term reliability test.

8.1.3 TCA Run 527-2A

Run 527-2A commenced on January 18, 1974, following the removal of the soft solids from the walls (inlet slurry spray nozzles area) and from the bottom of the Koch tray (the mist eliminator was not cleaned). It was a scheduled short-term run to determine whether certain changes in the scrubber internal configurations could minimize the mist eliminator plugging problem and to observe the effect of the changes on SO_2 removal and limestone utilization. The modifications included raising the Koch tray outlet weir height from 2 to 3 inches, using two beds (3 grids) with 7 1/2 inches of spheres per bed, and removing the four inlet slurry spray nozzles to minimize spray generation (slurry was introduced through the open nipples of the existing spray header).

The results of the changes were inconclusive and the run was terminated after 133 operating hours. The slurry carryover to the Koch tray and the mist eliminator appeared to be equal to or greater than the carryover observed during Run 526-2A.

The mist eliminator plugging continued on the lower vanes, and the free flow area was reduced by an additional 50 percent (for a combined total of 65 percent for Runs 526-2A and 527-2A). It should be noted that the Koch tray, inadvertently, was not irrigated for a 2 hour period during the run.

An additional 20 mils of scale formed on the scrubber walls below the bottommost grid.

8.1.4 TCA Run 528-2A

Run 528-2A was started on February 6, 1974, following a complete cleaning of the system. The run was intended to be of short duration and was made using raw water only for Koch tray irrigation. The Koch tray effluent was routed to the sewer. The purpose of the run was to observe the effect of irrigation with raw water, versus raw water plus clarified liquor, on the mist eliminator scale and solids deposition. Scrubber internal configurations were returned to Run 526-2A conditions (2 inch Koch tray outlet weir height, use of inlet slurry spray nozzles, three-bed operation). The HDPE spheres were replaced with new, improved TPR spheres with reinforced seams and with 5 inches of spheres in each bed. A dual strainer (by Elliot Co.) was installed in the scrubber feed slurry loop to prevent the inlet spray nozzles from plugging by debris.

The run was terminated on February 26 after 425 hours of operation, and the appearance of the system was generally good. The top of the Koch Flexitray was covered with approximately 20 mils of dust type solids. The mist eliminator was free of scale and solids with only a slight film of dust covering the inlet vanes. The pressure drop across the mist eliminator and Koch Flexitray had not increased during the test. The bottom of the wash tray was relatively clean.

Evidence from this test showed that the potential for scale and solids deposits on the mist eliminator is decreased when the degree of sulfate saturation of the Koch Flexitray wash liquor is reduced.

It should be noted that excessive weepage from the Koch tray irrigation water caused the test to be made with a slightly open liquor loop (average discharged solids of 29 percent). This explains the relatively low calculated scrubber inlet liquor sulfate saturation of 110 percent (see Table 8-2).

8.1.5 TCA Run 529-2A

Run 529-2A was started on February 26, 1974. The test conditions were the same as for Run 528-2A, except that the Koch tray was irrigated with the available raw water makeup plus all clarified liquor at an approximately one to three ratio. The run was initially intended to be a long-term limestone test. However, an inspection on March 7 revealed that the lower vanes of the mist eliminator were approximately 19 percent plugged with scale and soft solids. This was considered to be significant after the relatively short period of time, and the run was terminated after only 213 operating hours.

Nearly all the TPR spheres were dimpled.* Eight spheres had failed (filled with slurry) in the bottom bed.

8.1.6 TCA Run 530-2A

Run 530-2A was started on March 28, 1974, after a thorough cleaning. The Koch tray was irrigated at a constant rate of 15 gpm, consisting of about 8 gpm makeup water and 7 gpm clarified liquor, with the purpose of achieving a high dilution of Koch tray irrigation liquor and, hence, minimizing the mist eliminator and Koch tray scaling potential (see Run 528-2A).

The run was originally intended to be a long-term reliability test. However, it was terminated after only 476 operating hours when a rapid increase in pressure drop across the Koch tray occurred. An inspection revealed heavy scale and solids deposits on top of the Koch tray. A clarifier rake malfunction (which was not discovered until April 10) caused heavy solids carryover in the clarifier overflow for about two days. The solids carryover and the lower (15 gpm) Koch tray flush rate probably resulted in the settling of solids on the Koch tray. Subsequent use of the centrifuge for slurry dewatering resulted in centrate containing about 0.5 wt % of solids, which may have contributed to further settling of solids on the Koch tray.

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*This partially collapsed condition is considered normal by the supplier due to pressure and temperature cycling between operating periods and shutdowns.

The mist eliminator was heavily plugged. Inspection on April 9 (after 290 hours of operation) showed an estimated overall restriction of 8 percent which then increased rapidly in 186 hours to 44 percent at the end of run.

Approximately 100 TPR spheres (0.4 percent of the total inventory of the system) failed at the seams during the run.

8.1.7 TCA Run 531-2A

Run 531-2A was begun on May 10, 1974, after a thorough cleaning. Magnesium oxide was added to the effluent hold tank in an attempt to operate in the sulfate unsaturated mode.* Also, the TCA slurry header was lowered four feet in an attempt to reduce the amount of slurry droplet entrainment to the Koch tray.

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*Results from the EPA pilot facility at Research Triangle Park (Reference 12) have shown that it is possible to operate limestone and lime wet-scrubbing systems with liquors "unsaturated" with respect to calcium sulfate, thereby completely eliminating the potential for gypsum scaling. This is accomplished by controlling, within given limits, the total oxidation of sulfite to sulfate and the amount of dissolved sulfate. Under these limits, the sulfate formed by oxidation is purged, without crystallization, as a "solid solution" within the precipitated $CaSO_3$. The amount of sulfate which can be purged in this manner is related to the sulfate activity in the scrubbing liquor, which can be increased by addition of magnesium ion. The required magnesium addition for unsaturated operation appears to be higher for limestone systems than for lime systems and also increases as the concentration of chlorides in the process liquor increases.

The run was terminated after 1088 operating hours due to increasing pressure drop across the mist eliminator, Koch tray, and bottommost TCA bed. Inspection revealed considerable scale and solids deposits on the Koch tray, mist eliminator, and bottom grid. The mist eliminator was 75 percent plugged at the inlet edge and within the first pass. Scale deposits were limited to the first two passes.

Heavier than usual solids buildup was observed on the walls between the slurry spray nozzles and the steam sparger. This could be due to insufficient wetting of the walls by entrained slurry resulting from the lowering of the slurry spray header.

The run had never attained steady state (i.e., the desired magnesium ion concentration of 10,000 ppm was not reached), and the final magnesium concentration of 5,000 ppm in the process slurry was insufficient to attain unsaturated operation.

A total of 638 TPR spheres (2.4 percent of the starting inventory) failed at the seams during the run. The wear of the intact spheres varied from no measurable loss in the top bed to a 6.5 percent weight loss in the bottom bed for over 2000 hours of operation.

8.1.8 TCA Run 532-2A

Run 532-2A was begun on July 17, 1974, after the system was cleaned. Again, magnesium oxide was added to the effluent hold tank in an attempt to operate in the sulfate unsaturated mode at a 10,000 ppm level of magnesium ion in the process slurry. The scrubber recirculation liquor rate was increased from 1200 to 1700 gpm.

Also, a closed recycle irrigation liquor loop was provided for the Koch tray/mist eliminator system, which included provision for mist eliminator underwash (∼8 gpm fresh water plus ∼7 gpm recycle liquor). The Koch tray recycle irrigation rate was set at 35 gpm. The clarifier liquor, which had been used for Koch tray irrigation during the previous tests, was routed directly to the effluent hold tank.

Because of relatively high saturation (140 percent) of the inlet scrubber slurry and the liquor in the wash tray loop, an inspection was made on July 29, after 258 operating hours. About 200 mils of thick scale covered the walls below the bottommost grid, and the top of the Koch tray was covered with 12 mils of scale. The free flow area of the mist eliminator was 1 to 2 percent plugged with solids within the first and second passes.

About 4000 TPR spheres (15 percent of the total inventory) were found floating in the downcomer. They had passed through the bottom grid.[*]

In view of the above problems, the run was terminated. Note that the SO_2 removal efficiency for this test averaged about 98 percent, as compared with 84 percent for the previous test, due to the addition of magnesium (see Table 8-1).

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[*] The 1-1/2 inch TPR spheres can pass through the bar-grids supplied by UOP when they become dimpled on both sides.

8.1.9 TCA Run 533-2A

Run 533-2A was started on August 6, 1974, after a thorough cleaning of the system. The recirculating slurry rate was reduced from 1700 to 1200 gpm,* the used TPR spheres in the three beds were replaced with new ones, and the percent solids recirculated was increased from 8 to 15 percent. The Koch tray/mist eliminator system was the same as in the previous test, with a closed recycle irrigation liquor loop for the Koch tray and mist eliminator underwash. The scrubber slurry magnesium ion concentration was maintained at 10,000 ppm. The scrubber inlet liquor, however, remained supersaturated with respect to sulfate (see Table 8-2).

The run was terminated after 332 operating hours when an inspection showed that the underside of the wash tray was covered with up to 60 mils of scale over 40 percent of the tray area. The top surface of the tray was coated with from 50 to 100 mils of scale. The mist eliminator was 12 percent plugged with scale/solids deposit, primarily in the second and third passes. Also, the walls between the steam sparger and the slurry spray nozzles had up to 2 inches of solids deposit.

8.1.10 TCA Run 534-2A

Run 534-2A was started on September 3, 1974, after the system had been cleaned. It was decided to abandon, for the time being, attempts to operate in the sulfate unsaturated mode with the addition of magnesium oxide until further exploratory tests were conducted at the EPA pilot facility in Research Triangle Park.[*] Therefore, conditions for Run 534-2A were chosen similar to those of Run 526-2A, which had been in operation for 1190 hours with no apparent scaling problem on the top of the Koch tray. The underside of the mist eliminator was washed continuously with 15 gpm diluted clarified liquor ($\sim$8 gpm makeup water plus $\sim$ 7 gpm clarified liquor), while the Koch tray was irrigated with the remaining $\sim$8 gpm of clarified liquor plus the 15 gpm mist eliminator wash. The main differences between Runs 534-2A and 526-2A were, therefore, the addition of direct mist eliminator underwash and the four feet lower elevation of the inlet slurry spray header. In order to reach the expected steady state chloride concentration quickly, $CaCl_2$ was added to the system before startup.[**]

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*The liquor rate was reduced because of increased erosion of steel piping during the previous test and because the high liquor rate may have contributed to forcing the dimpled spheres through the bar-grids.

Run 534-2A was terminated after 100 on-stream hours due to scale buildup on the Koch tray. The top of the tray, including the valve caps, was almost completely covered with from 10 to 15 mils of scale. About 2 percent of the mist eliminator flow area was restricted by solids. Also, about 30 percent of the Koch tray underside surface was covered with solids, reaching a maximum thickness of 1 1/2 inches.

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[*] Further testing at the EPA pilot facility (see Reference 12) has indicated that a decrease in scrubber effluent residence time (i.e., an increase in solid solution precipitation rate) from 12 to 5 minutes would result in unsaturated operation for the conditions tested.

[**] It normally takes a number of weeks for the chloride level in the process slurry to reach a steady state value when beginning a run with raw water. The process slurry was dumped at the beginning of Run 534-2A to dispose of the large quantity of magnesium ion in the system.

As in the previous run, the walls between the steam sparger and the slurry spray nozzles had up to 2 inches of solids deposit.

8.1.11 TCA Run 535-2A

Run 535-2A was begun on September 12, 1974, after the system had been cleaned. The test conditions were nearly identical to Run 534-2A, with the added condition that a minimum clarified liquor return flow rate of 15 gpm was to be maintained for Koch tray irrigation and mist eliminator wash. In maintaining this rate, the fluctuating bleed flow to the clarifier resulted in, at times, only 12 to 13 percent solids (as compared with the desired 15 percent) in the recirculating slurry. Therefore, the effluent residence time was increased from 12 to 15 minutes, in order that the sulfate saturation of the scrubber liquor remain below 135 percent at all times (see Figure 7-2). Also, about 12 percent more make-up water was available for mist eliminator/Koch tray irrigation because of the elimination of seal water from a flue gas cooling spray pump.

After 158 hours of operation, an inspection showed about 15 mils of scale covering about 25 percent of the top of the Koch tray and relatively heavy solids accumulation (up to two inches thick in some areas) on the underside of the tray. The mist eliminator was about 5 percent plugged with solids (mostly fly ash) on the lower vanes. The walls between the steam sparger and the slurry spray nozzles had up to 4 inches of solids deposit. The run was continued.

After 316 hours of operation, a second inspection revealed that the scale had disappeared from the top of the Koch tray and that the mist eliminator was only 1 to 2 percent plugged with scattered solids (mostly fly ash) on the lower vanes. The bottom of the Koch tray, however, still had heavy solids accumulation. At this time, it was found that the steam pressure in the Koch tray steam sparger (see Figure 3-2) had drifted to 50 psig from an original setting of 125 psig. The steam pressure was reset and the run continued.

After 431 hours of operation, a third inspection showed that the top of the Koch tray was still clean and that the mist eliminator was practically clean (approximately one percent plugged with scattered solids on the bottom vane). The solids accumulation on the underside of the Koch tray had been substantially reduced, with 30 percent of the underside clean to metal. However, solids buildup on the walls between the steam sparger and the slurry spray nozzles had increased to a maximum thickness of 8 inches in some areas.

After 786 hours of operation, a fourth inspection showed that the top of the Koch tray was still clean and the mist eliminator again practically clean (approximately one percent plugged with scattered solids on the bottom vane). The solids accumulation on the underside of the Koch tray was slightly increased, with 20 to 25 percent of the underside clean. The solids buildup on the walls between the steam sparger and the slurry spray nozzles had further increased. The maximum deposit in one area had reached 15 inches in thickness. Approximately 30 mils of scale had accumulated on the grids during the 786 hours of operation. There was no measurable increase in pressure drop across the beds, Koch tray, or mist eliminator. The run was continued following the 786 hour inspection.

The average wear of the TPR spheres, for 1200 hours of operation, was about 4 percent.

8.2 MATERIAL BALANCES

The results of four material balances for calcium and sulfur during limestone reliability testing calculated over continuous on-stream operating periods are given in Table 8-3. The method of calculation is identical to the method used during reliability verification testing (see Section 7.5).

The computed inlet and outlet rates for calcium and sulfur are in good agreement. The average stoichiometric ratios based on solids analyses are probably more accurate than the values based on limestone addition rate and SO_2 absorption, due to uncertainties in the measurement of limestone slurry feed rate. The ionic balances for the bleed stream solids analyses, from which the calcium and sulfur discharge rates were calculated, averaged less than +4 percent (more cations than anions).

During Run 531-2A, when magnesium oxide was added in an attempt to achieve unsaturated operation, the stoichiometric ratio values reported include sulfur in the liquid but not magnesium since the material balance is only for calcium and sulfur. Stoichiometries based on both magnesium and calcium are reported in Table 8-1.

Table 8-3

SUMMARY OF MATERIAL BALANCES FOR SULFUR AND CALCIUM FROM LIMESTONE RELIABILITY TESTS

Run No.	Material Balance Period, hours	Sulfur Balance			Calcium Balance			Average Stoichiometric Ratio, Moles Ca Added/Mole SO_2 Absorbed	
		SO_2 Absorbed, lb-moles/hr	SO_x in Slurry Discharged, lb-moles/hr	Percent Error	Ca in Limestone Feed, lb-moles/hr	Ca in Slurry Discharged, lb-moles/hr	Percent Error	Based on Limestone Added and SO_2 Absorbed	Based on Slurry Analysis
526-2A	432	5.1	5.5	+ 7	8.1	8.0	-1	1.60	1.46
531-2A	352	4.7	5.1	+ 8	7.1	7.4	+4	1.50[a]	1.45[a]
531-2A	563	4.9	4.3	-14	4.5	4.5	0	0.93[a]	1.05[a]
535-2A	472	5.8	6.1	+ 5	8.5	9.1	+7	1.47	1.49

[a] Does not include magnesium.

8.3 CONCLUSIONS

8.3.1 Scrubber Internals Operability

Both the limestone reliability verification and reliability test results have shown that scrubber internals can be kept relatively free of scale if the sulfate (gypsum) saturation of the scrubber liquor is kept below about 135 percent. This can be accomplished with the proper selection of percent solids recirculated, effluent residence time, and liquid-to-gas ratio (see Figure 7-2). The data indicate that, at approximately 15 percent solids recirculated, 10 minutes effluent residence time, and 73 gal/mcf liquid-to-gas ratio, the scaling of the TCA internals will not become a problem in maintaining long-term system operation. For example, the four bar-grids in the TCA were covered with only 10 to 14 mils of scale after 1190 hours of operation in Run 526-2A.

A significant recent problem in the TCA has been associated with solids buildup on the walls between the steam sparger and the slurry spray nozzles (see Runs 531-2A through 535-2A), which originated after the slurry spray nozzles had been lowered by four feet. It is hypothesized that the solids buildup is due to insufficient wetting of the walls by entrained slurry. The problem may be corrected, therefore, by washing the walls between the tray and nozzles or by raising the nozzles to their original position. Such a wash system will be tried, and, if unsuccessful, the slurry nozzles will be raised.*

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*During the later portion of Run 535-2A, which was in progress at this report writing, a single nozzle Koch tray underwash utilizing the Koch tray effluent was installed and the steam sparger was removed. The single nozzle underwash has been successful in keeping the underside of the Koch tray as well as the scrubber walls below the tray free of solids buildup.

HDPE spheres had an operating life of about 2000 hours before eroding through and filling with slurry. TPR spheres showed a weight loss of only six percent after 2500 hours. At this erosion rate, a service life approaching one year would be anticipated for the TPR spheres. The TPR spheres tend to dimple, however, and can slip through the supporting bar-grids. This can be corrected by respacing the bar-grids.

There has been no measurable erosion of the bar-grids in the TCA after more than 5000 hours of operation.

8.3.2 Koch Tray/Mist Eliminator Operability

The most significant reliability problem encountered during the TCA limestone reliability tests has been associated with scaling and/or plugging of the Koch Flexitray and bottom vanes of the chevron mist eliminator (see Figures 3-2 and 3-4).

Run 528-2A showed that the mist eliminator and top surface of the Koch tray can be kept relatively free of scale if the irrigation liquor is low in sulfate saturation.

Run 526-2A showed that the top of the Koch tray can be kept relatively free of scale if it is irrigated with the available raw water makeup and clarified liquor, provided the mixture is maintained below the critical sulfate saturation level of approximately 135 percent. The run was terminated prematurely, after 1190 hours, due to excessive wear on the HDPE spheres and plugging (with debris) of the scrubber slurry nozzles.

The present Run 535-2A has been in operation for over 900 hours without any significant scaling or plugging of the top of the Koch tray or mist eliminator surfaces. The test conditions for this run are similar to those for Runs 526-2A and 529-2A, with the exception of direct mist eliminator underwash with raw water. It is likely that long-term reliability of this mist elimination system would be realized at the run conditions tested. Efforts to simplify the mist elimination system and to achieve reliability operation at higher gas velocities will be made during the Advanced Test Program.

Section 9

LIME RELIABILITY TEST RESULTS

Performance and analytical data from the venturi/spray tower system lime reliability testing at the Shawnee facility are presented in this section, along with an evaluation of each reliability test and the conclusions drawn, to date, from the testing.

9.1 PERFORMANCE DATA AND TEST EVALUATION

A summary of the test conditions and results for each of the venturi/spray tower lime reliability tests is presented in Table 9-1, along with the run philosophies. A summary of the scrubber inlet liquor analytical data for a majority of the tests is presented in Table 9-2, along with the calculated percent sulfate saturations.* Properties of coal and lime used during these tests can be found in Appendix C. Essential operating data for all of the venturi/spray tower lime reliability tests are graphically presented in Appendix I. An evaluation and discussion of each test is presented in the following sections.

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*The sulfate saturations and analytical data are for an average inlet gas SO_2 concentration of 2800 ppm. The effect of inlet gas SO_2 concentration on sulfate saturation is discussed in the following sections.

Table 9-1

SUMMARY OF LIME RELIABILITY TESTS ON VENTURI/SPRAY TOWER SYSTEM

Run No.	601-1A			602-1A	603-1A
Start-of-Run Date	10/9/73			1/15/74	4/2/74
End-of-Run Date	1/8/74			4/1/74	4/19/74
On Stream Hours	2153			393	396
Gas Rate, acfm @ 330°F	25,000			25,000	25,000
Spray Tower Gas Vel, fps @ 125°F	6.7			6.7	6.7
Venturi/Spray Tower Liquor Rates, gpm	600/1200			600/1200	600/1200
Spray Tower L/G, gal/mcf	60			60	60
Percent Solids Recirculated	7-9			7.5-9.5	13.5-16
Effluent Residence Time, min	12			12	12
Solids Disposal System	Clarifier Only (10/9-11/7)	Clarif & Intermittent Filter (11/7-12/15)	Clarifier & Filter (12/15-1/8)	Clarifier & Filter	Clarifier & Filter
Stoichiometric Ratio, moles Ca added/mole SO_2 absorbed	1.01-1.28	1.02-1.18	1.04-1.19	1.02-1.18	1.00-1.13
Avg % Lime Utilization, 100x moles SO_2 abs./mole Ca added	87	91	90	91	94
Inlet SO_2 Concentration, ppm	1600-3900	1600-4000	2100-4400	2100-3800	2100-4300
Percent SO_2 Removal	68-91	75-95	75-95	87-97	85-98
Scrubber Inlet pH Range	7.4-8.5	7.5-8.5	7.7-8.4	7.6-8.3	7.8-8.2
Scrubber Outlet pH Range	4.7-5.5	4.7-5.5	4.8-5.3	4.9-5.4	4.8-5.3
Percent Sulfur Oxidized	10-30	10-30	10-30	5-28	12-22
Loop Closure, % Solids Dischg.	20-26	20-27	42-52	42-48	46-54
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	150	120	180	165	135
Dissolved Solids, ppm	5700-7500	4600-7300	9800-12,300	9500	8200-10,900
Total ΔP Range, Excluding Mist Eliminator in. H_2O	11.0-11.5	11.0-12.0	11.7-12.3	11.0-12.0	11.0-12.0
Venturi ΔP, in. H_2O	9	9	9	9	9
Mist Eliminator ΔP, in. H_2O	0.55-0.70	0.60-0.90	0.90-1.65	0.65-0.73	0.56-0.72
Absorbent	Lime slurried to 20 wt% with makeup water and added to EHT.			Lime slurried to 20 wt% with makeup water and added to EHT.	Lime slurried to 20 wt% with makeup water and added to EHT.
Mist Eliminator	10/9 - 12/15: Bottom washed with available makeup water (~14 gpm) plus available clarified liquor (~26 gpm). Continuous wash rate of 0.8 gpm/ft². 12/15 - 1/8: Bottom washed with available makeup water (~5 gpm) plus available clarifier liquor (~45 gpm). Wash rate of 1 gpm/ft² on cycle of 3-1/2 min on/1-1/2 min off. Also, top was washed once/wk with fresh water for 5 min during last 4 wks.			Bottom washed with available makeup water (~5 gpm) plus available clarified liquor (~34 gpm). Wash rate of 1 gpm/ft² on cycle of ~ 4 min on/1min off.	Bottom washed with available makeup water (~5 gpm) plus available clarified liquor (~21 gpm). Wash rate of 1 gpm/ft² on cycle of ~ 1-1/2 min on/1-1/2 min off.
Scrubber Internals	All nozzles (7/header) on top 3 headers sprayed downward. Bottom header nozzles (7) sprayed upward.			All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.
System Changes Before Start of Run	System (scrubber and mist eliminator) cleaned.			System cleaned chemically (Na_2CO_3/sugar/limestone/flyash soln.) followed by mech. cleaning. EHT sealed. Installed external combustion reheater. Changed nozzles on bottom spray header to spray downward instead of upward. Capped middle nozzles on bottom header.	Mist eliminator cleaned.
Method of Control	Scrubber inlet pH controlled at 8.0 ± 0.2			Scrubber inlet pH controlled at 8.0 ± 0.2	Scrubber inlet pH controlled at 8.0 ± 0.2
Run Philosophy	Initially started as lime reliability verification test. Subsequently, due to apparent reliability of the run, decision was made that test continue as long-term reliability test.			Intended long-term. Sealed EHT in attempt to reduce sulfite oxidation and thereby degree of sulfate saturation.	Intended long-term. Recirculated 15% solids in attempt to reduce degree of sulfate saturation. EHT sealed.
Results	Routine inspection on 11/7/74 showed system was generally clean after 666 hours of operation with clarifier only for solids disposal. Run was terminated on 1/8/74 due to ID fan vibration and rapidly increasing pressure drop across mist. elim. Sulfate based scale formed on most scrubber walls and in slurry piping. Top of mist eliminator 80% plugged with solids that fell from outlet duct-work. Mist eliminator top vanes heavily scaled (300 mils avg.).			Run terminated due to scale (125 mils avg) and solids deposits on mist eliminator top vanes. Sulfite oxidation and sulfate saturation were not reduced. Steady state operation not achieved.	Degree of sulfate saturation was reduced, but run was terminated due to scale (40 mils avg.) and solids buildup on the mist eliminator top vanes.

Table 9-1 (continued)

SUMMARY OF LIME RELIABILITY TESTS ON VENTURI/SPRAY TOWER SYSTEM

Run No.	504-1A	505-1A	506-1A	508-1A
Start-of-Run Date	4/26/74	7/31/74	8/7/74	8/21/74
End-of-Run Date	7/19/74	8/6/74	8/14/74	9/17/74
On Stream Hours	1828	141	170	[illegible]
Gas Rate, acfm @ 330°F	25,000	25,000	25,000	25,000
Spray Tower Gas Vel. fps @ 125°F	8.7	8.7	8.7	[illegible]
Venturi/Spray Tower Liquor Rates, gpm	min. (~100)/1200	min. (~100)/1200	min. (~100)/1200	600/1200
Spray Tower L/G, gal/mcf	50	50	50	50
Percent Solids Recirculated	7.5-9.0	8.0-9.3	7.7-9.0	7.7-9.4
Effluent Residence Time, min.	17	17	17	12
Solids Disposal System	Clarifier & Filter	Clarifier & Filter	Clarifier	Clarifier & Filter
Stoichiometric Ratio, moles Ca added/mole SO_2 absorbed	1.03-1.30	1.10-1.17	1.10-1.14	1.06-1.24
Avg % Lime Utilization, 100x moles SO_2 abs./mole Ca added	88	88	89	87
Inlet SO_2 Concentration, ppm	2000-3800	2500-3300	2400-3200	2000-3750
Percent SO_2 Removal	70-92	73-81	67-79	75-95
Scrubber Inlet pH Range	7.7-8.4	8.8-9.2	7.8-8.2	7.6-8.4
Scrubber Outlet pH Range	4.5-5.4	4.9-5.1	5.0-5.2	4.9-5.1
Percent Sulfur Oxidized	8-30	12-28	12-22	12-28
Loop Closure, % Solids Dischg.	50-60	48-52	18-21	48-58
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	130	115	120	130
Dissolved Solids, ppm	11,600-13,700	6,000-7,400	5,000-7,000	7,500-9,500
Total ΔP Range, Excluding Mist Eliminator, in. H_2O	3.3-3.8	3.2-3.9	3.6-3.7	11.5-12.0
Venturi ΔP, in. H_2O	Plug 100% open	Plug 100% open	Plug 100% open	9
Mist Eliminator ΔP, in. H_2O	0.70-1.75	0.80-0.86	0.78-0.86	0.75-0.97
Absorbent	Lime slurried to 20 wt % with makeup water and added to scrubber downcomer.	Lime slurried to 20 wt% with makeup water and added to scrubber downcomer.	Lime slurried to 20 wt% with makeup water and added to scrubber downcomer.	Lime slurried to 20 wt% with makeup water and added to scrubber downcomer.
Mist Eliminator	Bottom washed with available makeup water (~5 gpm) plus available clarified liquor (~15 gpm). Wash rate of 1 gpm/ft² on cycle of ~3 1/2 min on/1 1/2 min off.	Bottom washed with available makeup water only (~5 gpm). Wash rate of 0.4 gpm/ft² on cycle of ~1 min on/4 min. off.	Bottom washed continuously with 15 gpm (0.3 gpm/ft²) raw water only. (Rate was greater than available makeup water).	Bottom washed with available makeup water only (~5.5 gpm). Wash rate of 150 gpm (3 gpm/ft²) for approx. 4 min. every 4 hours.
Scrubber Internals	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.
System Changes Before Start of Run	Mist eliminator and outlet duct cleaned. Sealed EHT provided with N_2 gas purge. EHT overflow blanked. Lime slurry makeup added to scrubber downcomer.	System cleaned.	Mist eliminator cleaned.	Mist eliminator cleaned. Provided for Freon gas blanket over EHT.
Method of Control	Scrubber inlet pH controlled at 8.0 ± 0.2	Scrubber inlet pH controlled at 9.0 ± 0.2	Scrubber inlet pH controlled at 8.0 ± 0.2	Scrubber inlet pH controlled at 8.0 ± 0.2
Run Philosophy	Intended 2 wks. To observe sulfite oxidation and degree of sulfate saturation with lime add'n to downcomer, minimum slurry rate to venturi, sealed EHT purged with N_2 gas, and 8% solids recirculated.	Intended long-term. Control at higher pH in attempt to reduce sulfite oxidation and thereby degree of sulfate saturation. Wash mist eliminator with water only.	Intended short-term. Mist eliminator washed continuously with raw water only (at rate greater than available makeup water).	Int'd 2 wks, 12 min res time, venturi in service, EHT sealed with Freon. Mist elim. on 4 hr wash cycle. Observe effects of lime add'n to downcomer and sealed EHT (compare with Run 501-1A).
Results	Degree of sulfate saturation was about 130%. Solids from outlet duct fell to top of mist eliminator. Run was terminated due to heavy scale (500 mils avg.) and solids buildup on mist eliminator.	Run was terminated due to scale formation (up to 150 mils) on top mist eliminator vanes.	Run was terminated due to scale formation (50 mils avg.) on top mist eliminator vanes.	Run terminated due to slight increase in mist eliminator ΔP. Inspection revealed scale buildup (88 mils avg.) on the mist eliminator top vanes.

Table 9-1 (continued)

SUMMARY OF LIME RELIABILITY TESTS ON VENTURI/SPRAY TOWER SYSTEM

Run No.	609-1A
Start-of-Run Date	9/20/74
End-of-Run Date	10/2/74
On Stream Hours	277
Gas Rate, acfm @ 330°F	25,000
Spray Tower Gas Vel, fps @ 125°F	6.7
Venturi/Spray Tower Liquor Rates, gpm	600/1200
Spray Tower L/G, gal/mcf	60
Percent Solids Recirculated	7.9-9.0
Effluent Residence Time, min.	24
Solids Disposal System	Clarifier & Filter
Stoichiometric Ratio, moles Ca added/mole SO_2 absorbed	1.07-1.25
Avg % Lime Utilization, 100x moles SO_2 abs./mole Ca added	87
Inlet SO_2 Concentration, ppm	2250-3600
Percent SO_2 Removal	80-96
Scrubber Inlet pH Range	7.6-8.6
Scrubber Outlet pH Range	4.7-5.4
Percent Sulfur Oxidized	12-30
Loop Closure, % Solids Dischg.	47-52
Calculated % Sulfate Saturation in Scrubber Inlet Liquor @ 50°C	110
Dissolved Solids, ppm	8,000-10,000
Total ΔP Range, Excluding Mist Eliminator, in. H_2O	11.0-11.9
Venturi ΔP, in. H_2O	9
Mist Eliminator ΔP, in. H_2O	0.80-0.85
Absorbent	Lime slurried to 20 wt% with makeup water and added to scrubber downcomer.
Mist Eliminator	Bottom washed with makeup at 2.7 gpm/ft² for ~8 min every 4 hrs. Simultaneous top wash with remaining makeup at 1 gpm/ft² through a single nozzle covering about 14 ft². Total makeup ~5 gpm avg.
Scrubber Internals	All nozzles on 4 headers sprayed downward. 7 nozzles/header on top 3 headers. 6 nozzles on bottom header.
System Changes Before Start of Run	Mist eliminator and outlet duct cleaned. A single nozzle installed to provide top wash for one section of mist eliminator and several holes drilled in the top vanes of a second section.
Method of Control	Scrubber inlet pH controlled at 8.0 ± 0.2.
Run Philosophy	Intended 2 wks. To observe the effect of mist eliminator top wash (on one section) and the effect of increased residence time on sulfate saturation.
Results	Run terminated as planned. Sulfate saturation reduced to 110%. Mist eliminator top vanes clean where top washed.

Table 9-2

AVERAGE SCRUBBER INLET LIQUOR COMPOSITIONS AND CALCULATED SULFATE SATURATIONS FOR VENTURI/SPRAY TOWER LIME RELIABILITY TESTS

Run No.	Percent Solids Recirculated	Effluent Residence Time, min.	Percent Solids Discharged	Percent Sulfur Oxidized	Scrubber Inlet pH Range	Inlet Liquor Species Concentrations, mg/l (ppm)									Calculated Percent Sulfate Saturation at 50°C[(c)(d)]
						Ca^{++}	Mg^{++}	Na^{+}	K^{+}	$SO_3^{=}$	SO_4	$CO_3^{=}$	Cl^{-}	Total	
601-1A[(a)]	7-9	12	20-26	10-30	7.4-8.6	1900	140	60	80	90	2000	20	2100	6400	150
601-1A[(b)]	7-9	12	42-52	10-30	7.5-8.5	3100	200	80	230	60	2300	25	4500	10,500	180
603-1A	13.5-16.0	12	46-54	12-22	7.8-8.2	2880	190	90	330	60	1670	5	4770	9990	135
604-1A	7.5-9.0	17	50-60	8-30	7.7-8.4	3200	400	80	275	50	2000	10	5700	11,700	130
605-1A	8.8-9.2	17	48-52	12-28	8.8-9.2	2200	50	60	180	50	1450	5	3070	7070	115
608-1A	7.5-9.0	12	48-58	13-24	7.9-8.4	2220	320	60	230	45	1920	10	3900	8700	130
609-1A	8-9	24	46-52	15-25	7.5-8.5	2680	310	60	120	40	1440	20	4200	8870	110

Note: Average concentrations are for steady-state operating periods.
Solids disposal system: Clarifier and filter.

(a) Solids disposal system: Clarifier

(b) Solids disposal system: Clarifier and filter

(c) The values of calculated sulfate saturation are for an average inlet gas SO_2 concentration of 2800 ppm.

(d) **Calculated Sulfate Saturation = (activity Ca^{++}) x (activity $SO_4^{=}$)/(solubility product at 50°C). A solubility product for $CaSO_4 \cdot 2H_2O$ of 2.2×10^{-5} was used (Radian Corporation, "A Theoretical Description of the Limestone-Injection Wet Scrubbing Process," NAPCA Report, June 9, 1970).**

9.1.1 Venturi/Spray Tower Run 601-1A

On October 9, 1973, a test (Run 601-1A) was begun on the venturi/spray tower system at the following major test conditions (see Table 9-1):

Spray Tower Gas Velocity	6.7 ft/sec
Venturi Liquid-to-Gas Ratio	30 gal/mcf
Spray Tower Liquid-to-Gas Ratio	60 gal/mcf
Percent Solids Recirculated	8
Effluent Residence Time	12 min.[*]
Scrubber Inlet Slurry pH (controlled)	8

This test was initially intended to be a lime reliability verification test, but due to apparently reliable operation, it was decided to continue the run under these conditions as a long-term reliability test.

The pH control level for the scrubber inlet slurry was chosen based on results of lime testing at the EPA pilot facility in Research Triangle Park, which indicated reasonable lime utilization and SO_2 removal at that level.

During the test, the chevron mist eliminator was washed on the underside both continuously (at a rate of 0.8 gpm/ft^2) and intermittently (1 gpm/ft^2, 3 1/2 minutes on/1 1/2 minutes off) with the available raw water makeup plus clarified liquor. Also, the mist eliminator was washed on the topside once per week with fresh water for 5 minute durations during the last four weeks of the test.

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[*] Twelve minutes was the minimum residence time obtainable in the effluent hold tank for this run.

Throughout the initial 666 hour portion of the run, the clarifier was used as the final dewatering device and the average percent solids discharged was 23 percent, which resulted in slightly open liquor loop operation. An inspection after 666 hours on November 7 showed that the mist eliminator bottom vanes were clean, while the top vanes were about 5 percent plugged with soft solids. The scrubbers were generally clean, with only a thin layer of scale (20 mils) on the upper half of the spray tower.

In order to operate under closed liquor loop conditions, the test was continued with the clarifier plus vacuum rotary drum filter (or centrifuge) in series. Problems with the filter cloth and mechanical difficulties with the centrifuge, however, resulted in intermittent operation of these pieces of equipment from November 7 to December 15. For the final 575 hours of testing (from December 15 through January 8), the filter operated satisfactorily, the average percent solids discharged increased from 23 to 47 percent, and the total dissolved solids increased from about 6500 to 10,500 ppm (see Table 9-2).

Run 601-1A was terminated after a total of 2153 hours (3 months) of operation, due to vibration in the ID fan and to rapidly increasing pressure drop across the mist eliminator. An inspection showed that the top of the mist eliminator was covered with solids that fell from the duct work above, restricting about 80 percent of the surface. In addition, about 1/8 to 1/2 inch thick scale formed in the middle and top vanes and about 5 percent of the bottom (inlet) vanes contained heavy (1/4 to

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[*] The venturi/spray tower system clarifier is undersized.

to 3/4 inch) scale. It is hypothesized that the heavy accumulation of solids in the outlet duct occurred when slurry droplet entrainment through the chevron mist eliminator wetted the duct walls during frequent reheater flame-outs.

Heavy scale had accumulated on the wall of the spray tower below the bottom header, while the middle section of the vessel was only slightly scaled. The venturi wall above the throat was clean, but scattered scale covered the plug. A light scale covered the venturi wall between the throat and flooded elbow, and the entire flooded elbow was covered with heavy scale. Also, the recirculating piping was scaled, with heaviest scale deposits in the pump suction areas. Scale also formed on the impeller eyes and tips of all the recirculating slurry pumps and on the lining of the casing of some of the pumps. It should be noted that scale formation in the scrubbers, circulating slurry piping, and pumps did not prevent continual operation of the system or necessitate termination of the run.

The formation of most of the scale on the scrubber walls and piping occurred between December 15 and January 8, when the system was operating under closed liquor loop conditions. The calculated average sulfate saturation of the scrubber inlet liquor during this period was 180 percent. This is contrasted with a calculated sulfate saturation of 150 percent for the inittial 666 hours of testing during open liquor loop operation (see Table 9-2).

An analysis of the test data during the final 575 hours of closed liquor loop operation shows that the calculated inlet liquor sulfate saturations are strong functions of inlet gas SO_2 concentration (or SO_2 absorption rate). For example, during test periods where the inlet gas SO_2 concentrations averaged 3200 and 2500 ppm, the calculated sulfate saturations averaged 225 and 140 percent, respectively.

9.1.2 Venturi/Spray Tower Run 602-1A

In preparation for the second lime reliability run, the system was partially cleaned chemically (Na_2CO_3/sugar/limestone/fly ash solution), followed by mechanical cleaning. All the stainless steel spray nozzles were replaced with identical full cone, stellite-tipped Bete nozzles (ST48FCN) and the original Hauck reheater, which had frequent flame-outs throughout the previous run, was modified to incorporate an external combustion chamber (designed by Bloom Engineering Co.).

Results from the EPA pilot facility in Research Triangle Park had indicated that sealing the effluent hold tank could reduce the sulfite oxidation and, thereby, the degree of sulfate saturation of the scrubbing slurry. In an attempt to duplicate this mode of operation, the effluent hold tank in the venturi/spray tower system was sealed prior to the start of Run 602-1A.

Run 602-1A was started on March 15, 1974. The mist eliminator was washed on the underside with the available raw water makeup and clarified liquor (in an approximately one to seven ratio) at a rate of 1 gpm/ft^2 in an intermittent operation (4 minutes on/1 minute off cycle).

After 393 operating hours, the run was terminated when it became apparent that sealing the effluent hold tank in this facility was not effective in reducing the degree of sulfate saturation of the scrubber inlet liquor. Although the sulfite oxidation had dropped somewhat (from about 20 to 17 percent), the calculated sulfate saturation at the termination of the test was 190 percent.

An inspection showed that a uniform (about 1/8 inch) scale covered most of the top and middle vanes of the mist eliminator. The bottom vanes were relatively clean. The walls of the spray tower were covered with a thin scale. The wall of the venturi below the plug was generally clean and no scale was deposited in the flooded elbow.

9.1.3 Venturi/Spray Tower Run 603-1A

Run 603-1A was started on April 2, 1974, after the mist eliminator was cleaned. The solids content of the recirculating slurry was increased from 8 to 15 percent in order to reduce the degree of scrubber liquor sulfate saturation. The mist eliminator was washed on the underside with the available raw water makeup and clarified liquor (in an approximately one to four ratio) at a rate of 1 gpm/ft^2 in an intermittent operation (1 1/2 minutes on/1 1/2 minutes off).

After 395 hours of operation, the run was terminated due to increasing pressure drop across the mist eliminator (from 0.55 inch H_2O at the start of the run to 0.70 inch H_2O). The mist eliminator had 50 to 70 mils of scale on the outlet edge and soft solids along the inlet edge of the top vanes. The middle and bottom vanes had light deposits of scale and soft solids. The venturi scrubber contained about the same amount of scale as before the start of the run, while there appeared to be slightly less scale on the spray tower walls and in the suction piping of the slurry pumps. The calculated sulfate saturation of the scrubber inlet liquor was 135 percent. This was a significant drop from the previous run's value of 180 percent saturation at 8 percent solids recirculated.

9.1.4 Venturi/Spray Tower Run 604-1A

In order to decrease the quantity of soft solids buildup on the mist eliminator, which had caused termination of the previous test, it was decided to drop back the percent solids recirculated from 15 to 8 percent for this run. To reduce the scrubber slurry sulfate saturation from the expected level of 180 percent (see Run 601-1A), (1) lime was added to the scrubber downcomer (vs. the effluent hold tank), (2) the effluent hold tank was purged (blanketed) with N_2, and (3) the venturi scrubber was used only for gas cooling (venturi plug 100 percent open with 100 gpm liquor flow rate).

It was theorized that the addition of lime to the downcomer quickly increases the pH of the scrubber outlet liquor, thereby precipitating calcium sulfite before the sulfite can be oxidized to sulfate in the liquid phase (the solubility of calcium sulfite is lower at higher pH). As mentioned previously, a reduction of liquor phase sulfite oxidation results in a reduction in sulfate saturation. It was further theorized that reducing the liquor flow to the venturi with a minimum flue gas pressure drop would minimize liquid atomization, oxygen absorption, and, consequently, oxidation.

Run 604-1A was begun on April 26, 1974, after the mist eliminator was cleaned. The mist eliminator was washed on the underside with the available raw water makeup and clarified liquor (at an approximately one to seven ratio) at a rate of 1 gpm/ft^2 in an intermittent operation (3 1/2 minutes on/1 1/2 minutes off). The effluent residence time was increased to 17 minutes, since this was the minimum time obtainable at the reduced total liquor rate of 1300 gpm (the venturi liquor rate had been reduced from 600 to 100 gpm).

The run was terminated after 1828 on-stream hours due to (1) increasing pressure drop across the mist eliminator (from 0.62 inch H_2O at start of run to 1.75 inches H_2O) and (2) gas flow control problems caused by solids accumulation on the ID fan inlet dampers. The top of the mist eliminator was 75 percent plugged with 150 to 200 pounds of loose solids which had fallen from the outlet duct. There was about 1/2 inch of scale on the top vanes and 1/4 inch of scale on the bottom vanes. Up to 2 inches of solids had accumulated in the outlet gas duct and six of the 14 fan damper blades were covered with 1 to 2 inches of solids.

The sulfite oxidation ranged from about 14 percent with N_2 purge over the effluent hold tank to about 19 percent without N_2 purge (from May 29 to June 5).* The calculated average sulfate saturation of the scrubber inlet liquor, however, was 130 percent. This was a significant drop from the saturation level of 180 percent during the closed liquor loop portion of Run 601-1A.

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*Oxygen concentrations in the effluent hold tank in the vicinity of the gas/liquid interface ranged from 15 to 20 percent, as compared with 21 percent for air. This suggests that sealing the tank and N_2 purging were not effective in reducing oxygen absorption in the effluent hold tank.

As in Run 601-1A, an analysis of the data showed that the calculated inlet liquor sulfate saturation was a strong function of the SO_2 absorption rate. For example, during test periods where the inlet gas concentrations averaged 2700 and 2900 ppm, the calculated sulfate saturations averaged 120 and 150 percent, respectively.

9.1.5 Venturi/Spray Tower Run 605-1A

Run 605-1A was started on July 31, 1974, after the mist eliminator was cleaned. The scrubber inlet liquor pH was raised from 8 to 9 only for this run to observe the effect of pH on sulfate saturation. The mist eliminator was washed intermittently with raw water makeup at a rate of 0.4 gpm/ft^2 on a 1 minute on/4 minute off cycle. As before, lime was added to the downcomer and the venturi liquor rate was set at 100 gpm with the venturi plug 100 percent open.

An inspection after 141 operating hours showed relatively heavy (up to 150 mils) scale on the top mist eliminator vanes and the run was terminated. As observed in previous runs, there was a moderate buildup of scale on the middle vanes (50 mils) and only a light dust film on the bottom vanes. No additional scale had formed in the spray tower during the run. The calculated average percent sulfate saturation of the scrubber inlet liquor was 115 percent. This can be compared with a level of 130 percent for Run 604-1A, which had a controlled scrubber inlet liquor pH of 8.0 (see Table 9-2).

9.1.6 Venturi/Spray Tower Run 606-1A

Run 606-1A was started on August 7, 1974, after the mist eliminator had been cleaned. The objective of the run, which was intended to be of short duration, was to investigate scale formation on the mist eliminator vanes with continuous washing on the mist eliminator underside with raw water at a rate of 0.3 gpm/ft^2. This raw water rate (15 gpm) is approximately three times the quantity normally used during closed liquor loop operation, and, therefore, the test was made under open liquor loop conditions (about 21 percent solids discharged). The scrubber inlet liquor pH was reduced from 9 to 8 for this test.

The run was terminated after 170 on-stream hours. About 95 percent of the trailing (top) surface of the mist eliminator vanes was covered with 30 to 70 mils of scale. As usual, there was light soft solids accumulation on the middle vanes and the bottom vanes were relatively clean. It should be noted that the scale growth rate on the top vanes (~50 mils/week) was about the same for this test as for all of the previous tests in which mixture of clarified liquor plus raw water were used for underside washing.

9.1.7 Venturi/Spray Tower Run 608-1A

Run 608-1A was started on August 21, 1974, after the mist eliminator had been cleaned. The main objective of the test was to investigate scale formation on the mist eliminator vanes with intermittent underside washing at high perssure (45 psig) using the available raw water makeup at a rate of 3 gpm/ft^2 for about 9 minutes every 4 hours. Also, the venturi scrubber was put back in service (at 600 gpm and 9 inches H_2O pressure drop) in order to investigate the effect of venturi operation (Runs 608-1A vs. 604-1A) and lime addition in the downcomer (Runs 608-1A vs. 601-1A) on scrubber liquor sulfate saturation.

The run was terminated after 610 hours of operation due to increasing pressure drop across the mist eliminator (from 0.75 inch H_2O at start of run to 0.95 inch H_2O). About 80 percent of the trailing surface of the top vanes was covered with scale, averaging 88 mils in thickness and resulting in approximately 3 percent pluggage of the free flow area. The middle and bottom vanes were, as usual, essentially clean (3 mils of dust coverage). Note that the average scale growth rate on the top vanes for this test (24 mils/week) was essentially half the average scale growth of the previous four tests.

The condition of the scale on the walls of the spray tower remained essentially unchanged, but the spiral tips of most of the spray nozzles were covered with 1/4 to 1/2 inch scale ("whiskers").

The calculated average sulfate saturation of the scrubber inlet liquor was 120 percent (see Table 9-2). This is the same as the calculated saturation for Run 604-1A and about 50 percent lower than the calculated saturation for Run 601-1A. Therefore, it may be concluded that, for these run conditions, venturi operation has little effect on sulfate saturation and the addition of lime to the downcomer (vs. lime to the effluent hold tank) significantly reduces the sulfate saturation of the process slurry.

9.1.8 Venturi/Spray Tower Run 609-1A

Run 609-1A was started on September 20, 1974, after the mist eliminator had been cleaned. The primary objective of the test was to evaluate the effect of topside mist eliminator washing on the formation of scale on the top mist eliminator vanes. The entire underside of the mist eliminator and a 14 ft^2 area on the topside was washed at high pressure (45 psig) with makeup water at a rate of 2.7 gpm/ft^2 for the underside and 1.0 gpm/ft^2 for the topside for about 8 minutes every 4 hours. Only a small section of the topside was washed because it was felt that water carryover from top sprays could possibly cause reheater overloading and fan problems.* Also the effluent residence time was increased from 12 to 24 minutes, for this test, in order to determine the effect of residence time on scrubber liquor sulfate saturation (Run 609-1A vs. 608-1A).

Run 609-1A was intended to be of short duration and was terminated after 278 hours of operation. The topside spray had been successful in drastically reducing the scale buildup on the top mist eliminator vanes. The washed area was essentially clean, with less than 1 mil of solids accumulation, compared with an average of 40 mils scale buildup on the rest of the topside surfaces.

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*Procedures for minimizing these problems, such as use of a sequential sectional wash of the topside of the mist eliminator or use of a second mist eliminator downstream of the topside sprays, will be investigated during the Advanced Test Program.

The calculated average sulfate saturation of the scrubber inlet liquor was 110 percent for the test (see Table 9-2). This value is about 20 percent lower than the calculated saturation for Run 608-1A. It may be concluded, therefore, that the effect of effluent residence time on sulfate saturation is similar for lime systems as for limestone systems (see Figure 7.2).

9.2 MATERIAL BALANCES

The results of five material balances for calcium and sulfur during lime reliability testing calculated over continuous on-stream operating periods are given in Table 9-3. The method of calculation is identical to the method used during reliability verification testing (see Section 7.5).

The computed inlet and outlet rates for calcium and sulfur are in fair agreement. The average stoichiometric ratios based on solids analyses are probably more accurate than the values based on lime addition rate and SO_2 absorption, due to uncertainties in the measurement of lime slurry feed rate. The ionic balances for the bleed stream solids analyses, from which the calcium and sulfur discharge rates were calculated, averaged less than +2 percent (more cations than anions).

Table 9-3

SUMMARY OF MATERIAL BALANCES FOR SULFUR AND CALCIUM FROM LIME RELIABILITY TESTS

Run No.	Material Balance Period, hours	Sulfur Balance			Calcium Balance			Average Stoichiometric Ratio, Moles Ca Added/Mole SO_2 Absorbed	
		SO_2 Absorbed, lb-moles/hr	SO_x in Slurry Discharged, lb-moles/hr	Percent Error	Ca in Lime Feed, lb-moles/hr	Ca in Slurry Discharged, lb-moles/hr	Percent Error	Based on Lime Added and SO_2 Absorbed	Based on Slurry Analysis
601-1A	400	6.2	5.9	- 5	6.4	6.7	+ 4	1.03	1.13
601-1A	456	6.3	5.5	-15	5.7	6.0	+ 5	0.91	1.09
602-1A	317	7.2	7.9	+ 9	6.7	8.6	+22	0.94	1.10
604-1A	894	5.8	5.9	+ 2	5.2	7.1	+27	0.91	1.20
606-1A	168	5.3	5.4	+ 2	4.7	6.1	+23	0.88	1.13

9.3 CONCLUSIONS

9.3.1 Scrubber Internals Operability

The lime and limestone reliability tests have shown that scrubber internals can be kept relatively free of scale if the sulfate (gypsum) saturation of the scrubber liquor is kept below about 135 percent. As with limestone, this can be accomplished with increased percent solids recirculated (Run 603-1A vs. 601-1A) and/or with increased effluent residence time (Run 609-1A vs. 608-1A). Moreover, the lime tests have shown that adding the lime to the scrubber downcomer (which corresponds to a small residence time tank in series with the larger effluent hold tank) can substantially reduce the sulfate saturation (Run 608-1A vs. 601-1A), allowing for operation at reduced percent solids and/or effluent residence time. Also, operating at higher scrubber inlet liquor pH appears to reduce the scrubber liquor sulfate saturation (Run 605-1A vs. 604-1A).

The lime tests have also shown that the sulfate saturation of the scrubber inlet liquor is a strong function of the inlet gas SO_2 concentration (SO_2 absorption rate). The data have indicated that a 100 ppm increase in SO_2 inlet concentration corresponds roughly to a 10 percent increase in sulfate saturation at the run conditions tested.

It should be noted that the 27 full-cone, stellite-tipped Bete nozzles in the spray tower have shown no signs of measurable erosion after approximately 4000 hours in slurry service.

9.3.2 Mist Eliminator Operability

The most significant reliability problem encountered, to date, during the venturi/spray tower lime reliability tests has been associated with scaling and/or plugging of the topmost vanes of the chevron mist eliminator (see Figures 3-1 and 3-4).

Runs 601-1A through 608-1A showed that the scale formation rate on the top mist eliminator vanes (25 to 20 mils/week) was relatively unaffected by the wash cycle, wash rate, or quality (sulfate saturation) of the wash liquor. Run 608-1A showed that intermittent washing with high pressure (45 psig) raw water at a rate of 3 gpm/ft^2 for 9 minutes every 4 hours gave results that were at least as good as results with continuous washing with relatively low pressure raw water at 0.3 gpm/ft^2 (Run 606-1A). Intermittent washing can be especially important if the availability of raw water makeup is restricted (e.g., at high percent solids discharged and/or high pump seal water usage).

Run 609-1A showed that intermittent topside and bottomside washing with high pressure raw water would most likely eliminate the scale accumulation problem on the top vanes of the existing mist eliminator (see Figure 3-4) and allow for long-term reliability of the system at the run conditions tested (see Table 9-1). However, the problems caused by entrainment of topside wash water will have to be evaluated.

The reliability of the mist eliminator with intermittent topside and bottomside washing using high pressure raw water has been further demonstrated in a recently completed 253 hour test (Run 610-1A). The scrubber and mist elimination systems were not cleaned before the test.

After a total of 531 operating hours (Runs 609-1A and 610-1A), the washed area of the top mist eliminator vanes was still clean compared with about 70 mils scale buildup on the rest of the topside vane surfaces.

Further tests with topside and bottomside wash and tests at higher gas velocities will be made during the Advanced Test Program.

Section 10

OPERATING EXPERIENCE DURING LIME/LIMESTONE TESTING

In this section, the operating experience during lime/limestone wet-scrubbing testing at the Shawnee facility is summarized. Also summarized are the results of a materials evaluation program conducted by TVA.

10.1 CLOSED LIQUOR LOOP OPERATION

Results at the Shawnee facility have shown that scaling potential, which is a primary factor affecting reliability, is significantly affected by the quantity of raw water input to the system, i.e., the greater the raw water input, the lower the scaling potential (see Section 7.3). To obtain significant and comparable reliability data, therefore, the scrubber systems must be operated in a "closed liquor loop" mode. Closed liquor loop operation is defined as operation in which the raw water input to the system is equal to the water normally exiting the system in the settled sludge and in the humidified flue gas. For lime/limestone wet-scrubbing systems, the solids concentration in the settled sludge is normally equal to or greater than 38 wt %.

Closed liquor loop operation was not achieved during the initial limestone factorial test period. Water input was excessive and sludge with less than 38 wt % solids had to be discharged from the systems. This was not considered a serious problem during factorial testing (see Section 6), but little information was gained about the effect of scaling potential on reliability during this period.

Sources of excessive water input included seal water used to flush the stuffing boxes (Hydroseals) on the slurry pumps, water quench sprays used to cool and saturate incoming gas, and water used to dilute the limestone slurry feed (10 to 20 wt % limestone).

The absorbent feed system was changed in November 1972, to provide slurry feeds with up to 60 wt % limestone concentration. During the five week boiler outage in February and March 1973, the Hydroseal slurry pumps were converted to a Centriseal type (stuffing box with air purge), and the TCA and Marble-Bed scrubbers were provided with process slurry gas cooling systems. As a result of these modifications, closed liquor loop operation has been maintained at the facility since the beginning of limestone reliability verification testing in March 1973.

10.2 MIST ELIMINATOR OPERABILITY

The most significant reliability problem encountered during the lime/limestone wet-scrubbing tests has been associated with the scaling and/or plugging of mist elimination surfaces.

It is hypothesized that mist eliminator scaling is caused predominently by SO_2 absorption into process liquor adhering to the mist eliminator surfaces, subsequent oxidation of the absorbed SO_2 species to sulfate, and the resultant precipitation of calcium sulfate. In addition, solids adhering to the mist eliminator surfaces will cause plugging and may also act as sites for additional scale formation. These problems may be alleviated by: (1) reducing the sulfate saturation of the mist eliminator wash liquor (e.g., utilizing raw water or subsaturated process liquor), (2) washing the mist eliminator at a sufficient rate to remove all impacted solids, (3) utilizing a wash tray to reduce the suspended solids concentration of the droplets impinging upon the mist eliminator, (4) using mist eliminators with improved draining characteristics (e.g., sloped mist eliminators), and (5) addition of softening or descaling agents. Most of these concepts have been tested to date at the Shawnee facility during the lime/limestone reliability sequences. These concepts will be discussed in the following sections.

10.2.1 Venturi/Spray Tower System

A three-pass, open vane, stainless steel, chevron type mist eliminator (see Figures 3-1 and 3-4) was used in the venturi/spray tower system during the latter half of the limestone reliability verification testing period and during the entire lime reliability testing sequence. A polypropylene chevron mist eliminator (see Figure 3-4), used during the early part of the limestone reliability verification testing period, was discarded after it was damaged by solids falling onto it from the outlet duct.

In the venturi/spray tower system, operating at a superficial gas velocity of 6.6 ft/sec, there has been a continuing problem of scale formation on the top mist eliminator vanes. A variety of washing configurations have been tried in order to alleviate this problem. Individual test runs are discussed in Section 9.2.2.

Underside washing only, either continuously with low pressure water at 0.3 gpm/ft^2 or intermittently with high pressure water at 3 gpm/ft^2 (9 minutes every 4 hours at 45 psig), was unsuccessful in eliminating scale formation on the top vanes. It was encouraging, however, that intermittent washing (0.1 gpm/ft^2 average rate) was as effective as continuous washing (0.3 gpm/ft^2) for removing soft solids. Intermittent washing may be required in closed liquor loop operation due to restrictions in the allowable raw water makeup to the scrubber system.

A combination of intermittent high pressure topside wash at 1 gpm/ft^2 and bottomside wash at 2.7 gpm/ft^2 (simultaneous top and bottom wash for 8 minutes every 4 hours at 45 psig) appeared to be successful in eliminating the scale accumulation on the upper mist eliminator vanes. However, entrainment of the topside wash water may be a problem. This will be investigated.

Future plans include testing a new sloped (cone-shaped) closed-vane chevron mist eliminator with underside washing, and testing the existing open-vane chevron mist eliminator with intermittent and sequential topside washing and with intermittent bottomside washing. A Koch Flexitray preceding the mist eliminator will be installed if long-term reliability cannot be achieved with the use of sprays only.

10.2.2 TCA System

The TCA mist eliminator system consisted of a Koch Flexitray in series with a six-pass, closed-vane, stainless steel, chevron type mist eliminator (see Figures 3-2 and 3-4) during both the limestone verification and the reliability testing.

At this report writing, a TCA run (Run 535-2A, see Table 8-1), operating at a superficial gas velocity of 8.6 ft/sec, has been in operation for over 900 hours without any significant scaling or plugging of the Koch tray or mist eliminator surfaces. It appears that long-term reliability of this mist eliminator system can be realized at the conditions used during this run.

For Run 535-2A, the underside of the Koch tray has been intermittently steam sparged (125 psig) for one minute every hour. The underside of the mist eliminator has been washed continuously with 15 gpm diluted clarified liquor (~ 9 gpm makeup water plus ~ 6 gpm clarified liquor), while the Koch tray has been irrigated with the remaining ~ 9 gpm of clarified liquor plus the 15 gpm mist eliminator wash. The main difference between Run 535-2A and earlier runs (in which there was some scaling and plugging of the lower vanes of the chevron mist eliminator) was that a minimum clarified liquor flow rate of 15 gpm has been maintained for Koch tray irrigation and mist eliminator wash, while recirculated solids concentration has been allowed to fluctuate between 12 and 15 percent. Previously, the clarified liquor rate had been allowed to fluctuate, while the recirculated solids concentration was maintained at 15 percent. A discussion of previous runs is presented in Section 8.3.2.

Future plans include the testing of the TCA mist elimination system at increased gas velocity (10 and 12 ft/sec) and testing of the 6-pass chevron mist eliminator with the Koch tray removed.

10.3 SCRUBBER INTERNALS

10.3.1 TCA Grid Supports

The original wire mesh grids (0.148 inch diameter stainless steel wires) deteriorated considerably during the approximately 3000 hours of operation in slurry service. Vibration caused by plastic sphere activity resulted in the rubbing together of the grid wires at their perpendicular junctions and the grids failed at several locations due to subsequent erosion of the wires in slurry service.

The wire mesh grids were replaced with sturdier "bar-grids" (3/8 inch in diameter stainless steel bars, 1-1/4 inch on centers) prior to the long-term limestone reliability testing. There has been no measurable erosion of the bar-grids in over 5000 hours of slurry service.

10.3.2 TCA Plastic Spheres

Until recently, a significant limiting factor in the long-term reliability of the TCA scrubber has been associated with the erosion and subsequent collapse of the UOP supplied HDPE spheres (sphere life was approximately 2000 hours). The collapsed spheres eventually filled with slurry and settled to the bottom of the support grids. Starting with Run 528-2A (see Section 8), an improved type of UOP supplied

TPR sphere[*] was used in the TCA beds. After approximately 2500 hours of operation, all the spheres were dimpled on one side, about 2.4 percent failed at the seam, and the weight loss averaged about six percent. It is estimated that these TPR spheres would not need replacement until after about a year of service. The problem of dimpled spheres falling through the bar-grids (see Run 532-2A in Section 8) may be solved by respacing the grids or using heavier spheres.

10.3.3 Nozzles

Initially, nozzle reliability at the test facility was greatly reduced by the frequent plugging of spray nozzles with foreign material (TCA spheres, marbles, debris, etc.) and the erosion of some spray nozzles by the abrasive solids in the circulating slurries. Nozzle plugging, however, was reduced substantially by placing covers over the open vessels in the scrubber systems and installing strainers in the circulating slurry lines.

Spray Tower. Limestone factorial testing in the spray tower started with the use of spiral tip, 316 SS, full cone, Bete No. ST24FCN nozzles (capacity: 12 gpm @ 10 psi) manufactured by Bete Fog Nozzles, Inc. Because of frequent plugging with slurry and/or debris, these nozzles were replaced in September 1972, with Bete No. ST32FCN nozzles (capacity: 21 gpm @ 10 psi). Plugging of the larger Bete nozzles was less frequent. Neither type of nozzle was in service long enough to determine wear rates.

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[*] The original supply of TPR spheres was defective and many of the spheres split at the seams. Subsequent batches were of much better quality.

To allow for increased liquor flow to the four-header spray tower, Bete No. TF48FCN stainless steel nozzles (capacity: 47 gpm @ 10 psi) were installed during the February 1973 boiler outage. Because of severe erosion of the stainless steel tips (average weight loss of approximately 28 percent in 4320 hours), they were replaced with identical stellite tipped ST48FCN nozzles in March 1974. No erosion of these nozzles has been noted after over 5000 operating hours.

Plugging of the spray nozzles with debris was greatly reduced by installing dual strainers (manufactured by Elliot Co.) in the circulating slurry lines in June 1973, and by sealing the effluent hold tanks in July 1974.

TCA. The large Spraco No. 1969F, full cone, 316 SS, open type slurry feed nozzles were replaced on October 1973 and again in September 1974, although erosion was only slight (no significant wear after 4900 hours at 5 psi pressure drop for the second set of nozzles).

Occasional partial plugging of the nozzles with large debris (half TPR spheres, parts of plastic insulation cover) was alleviated with the installation of a dual strainer (by Elliot Company) in the circulating slurry line in February 1974 and the sealing of the effluent hold tank in March 1974.

Marble-Bed. The 22 original slurry feed spray nozzles lined with Solathane 291 and equipped with internal Adiprine LD315 swirl vanes failed in various ways during the short-term limestone factorial testing. The swirl vanes in all 22 nozzles eroded, the liners of four bottom nozzles collapsed, and two bottom nozzles disintegrated. The nozzles frequently became plugged with slurry and debris.

The original slurry feed nozzles were replaced during the February 1973 boiler outage with improved nozzles supplied by Combustion Engineering (stronger Adiprine LD3056 lining with improved bonding using Thixon 1244 between the liner and the body of the nozzle and a locking groove to hold the vanes in place). The diffusion vanes of the 16 bottom spray nozzles failed during the initial limestone reliability verification test runs after 1060 hours of operation.

All 22 CE spray nozzles were replaced before limestone reliability verification Run 504-3A with Spraco No. 1736 hollow cone nozzles. These nozzles were in service for only 233 hours due to the discontinuation of testing on the system.

10.4 HOT-GAS/LIQUID INTERFACE

The hot (300 to 330°F) flue gas feed must be humidified before entering the neoprene rubber-lined TCA and Marble-Bed scrubbers to reduce the gas temperature below 190°F, the maximum permissible for liner protection. Normally, the gas temperature was reduced to about 150°F. Cooling of the feed gas was not required at the venturi scrubber inlet during normal operation since the venturi scrubber itself is an efficient humidifying device.

During open liquor loop factorial testing, raw water humidification sprays were used in the vertical duct leading down to the TCA and Marble-Bed scrubbers. Sootblowers were used in the horizontal section of the duct at the scrubber entrance. With this arrangement there was a continual problem of soft solids buildup at the hot-gas/liquid interface.

To facilitate closed-loop operation by minimizing raw water addition, the TCA and Marble-Bed scrubbers were provided with process slurry cooling systems during the boiler outage in February 1973.

The TCA system was equipped with a Venturi-Rod presaturator in the horizontal gas duct two feet upstream of the scrubber entrance. The performance of the Ventri-Rod was not satisfactory in the horizontal flow configuration (rapid buildup of soft solids occurred both on and downstream of the Ventri-Rod), and it was replaced during reliability verification Run 501-2A with a humidification section consisting of four full-cone Bete nozzles (ST24FCN) in the horizontal duct.

By subsequent careful selection of the proper size, orientation, location, and number of the spray nozzles, modification of the soot blower head (both nozzles leading at 45°), air blowing during forward travel only, and installation of a Y-strainer in the process slurry line to the cooling spray nozzles, the buildup of solids in the TCA inlet duct was essentially eliminated. These improvements resulted in the wet-dry interface being moved to within 12 inches of the scrubber entrance, where the accumulated solids could be easily blown into the scrubber and discharged through the 36 inch downcomer for reslurrying in the effluent hold tank.

On the Marble-Bed scrubber, modifications to the cooling slurry system resulted in moderate but encouraging results. The effectiveness of these modifications could not be verified due to the discontinuation of testing at the end of Run 503-3B in July 1973.

10.5 REHEATERS

Flue gas from the scrubber is reheated to prevent condensation and corrosion in the exhaust system, to facilitate isokinetic and analytical sampling, to protect the induced draft fans from solid deposits and droplet erosion, and to increase plume buoyancy.

The reheaters originally employed (Hauck Manufacturing Co.) were fuel oil fired units with separate combustion air supply and with combustion occurring in the flue gas stream. The reheaters were difficult to start and operate, and the combustion was incomplete. The latter resulted in a visible plume containing significant quantities of soot that made the interpretation of the outlet particulate data difficult and affected gas sampling by the Du Pont SO_2 photometric analyzers. Moreover, significant quantities of oil-soaked soot accumulated in the duct work which, on two occasions, resulted in fires. The difficulty appeared to result from quenching of the flame by the cold (128°F) flue gas before complete combustion could occur, and from operating with the same fuel oil nozzles over a wide range of flow rates.

As an expedience for operation, all three reheater systems were modified during the scheduled boiler outage in early 1973, using stainless steel sleeves (10 gage, 304 SS, 40 inches in diameter by 4 feet high) to provide approximately 50 cubic feet of isolated combustion zone for each reheater. In addition, the original turbulent mixing type fuel oil nozzles were replaced with mechanical atomizing nozzles. These modifications were effective in achieving complete combustion, but burner flame-out continued to be a problem.

To maintain operation consistent with the requirements for long-term sustained reliability, the reheater on the venturi/spray tower system was modified in March 1974 to include a fuel oil fired external combustion chamber (manufactured by Bloom Engineering Co.). The performance of this unit has been very satisfactory with excellent equipment reliability (i.e., minimal flame-outs and operating difficulties), essentially complete combustion, and improved fuel economy for over 4000 hours of service. Procurement arrangements have been initiated to provide an identical unit to reheat the outlet gas from the TCA scrubber.

10.6 FANS

Initially, considerable difficulty was experienced with the induced draft fans (manufactured by Zurn Industries). Some of the problems included high fan vibration, fan motor failure, fan damper control failure, and fan blade deformation. All of the problems, except for blade deformation, required repeated shutdowns of the affected scrubber systems.

The unacceptable high vibration problem of all three fans was greatly reduced in June 1972, by insulating the fan housing, adding additional bracing to the outboard pedestals, and welding balance weights on the fan shrouds. However, occasional high fan vibration continued to hinder scrubber operation, particularly on the venturi/spray tower system.

Stable flue gas flow control was difficult to achieve until the "fully open" to "full closed" fan damper response time was increased from 10 to 100 seconds with new actuators.

Erosion, corrosion, pitting, scaling, etc. have been negligible on all three fans. However, past operation has been with 125°F flue gas reheat to give a fan outlet temperature of 250°F. Future plans may include operation with reduced reheat. Prior to the commencement of the low reheat test runs, the outlet ducts and the stacks of both the venturi/spray tower system and the TCA scrubber will be insulated, and corrosion test coupons will be mounted upstream and downstream of the respective fans.

10.7 PUMPS

The majority of the pumps used at the Shawnee test facility in alkali slurry service are rubber-lined variable speed centrifugal pumps manufactured by Allen-Sherman-Hoff. Most of the original pumps had Hydroseals, but excessive consumption of seal water resulted in upsetting the slurry liquor loop water balance. The pumps were converted to air purged Centriseals during the boiler outage in February 1973.

Except for excessive seal water consumption, the Hydroseal pumps performed satisfactorily. When converted to Centriseal, however, the smaller pumps (less than 100 gpm) required pump discharge-to-suction recirculation lines to eliminate a vapor lock problem at low flow rates. In addition, frequent replacement of packing material and accelerated wear rates on shaft sleeves have been experienced with pumps using Centriseals. A program of testing hardened 316 stainless steel sleeves is currently underway.

In general, the rubber linings have shown excellent erosion-corrosion resistance characteristics and have remained in good condition. Bond failure between the metal casing and the rubber lining has occurred only once since the commencement of testing. On two occasions, the rubber lining was badly gouged by debris (in one case part of a slurry spray nozzle) entering the pumps from the suction tanks.

One stainless steel variable speed centrifugal pump was originally used in the limestone slurry addition system. Severe erosion of the housing and impeller were noted (with a corresponding loss of 20 percent pumping efficiency) in only twenty days of actual operation. Subsequently, this pump was replaced by individual Moyno pumps to each scrubber system. Operation of the Moyno pumps (stainless steel rotor and butyl rubber stator) has been satisfactory with only normal maintenance required.

10.8 WASTE SOLIDS HANDLING

The test facility is equipped to study alternative methods of waste solids dewatering and disposal. Separate clarifiers were provided for each scrubber system. A rotary drum vacuum filter and a horizontal solid bowl centrifuge are common to the three systems.

10.8.1 Clarifiers

The clarifiers are conventional solids contact units (manufactured by Dorr-Oliver) with a heavy duty rake and scraper mechanism supported from a bridge. The vessels are glassflake lined with a stainless steel rotating mechanism. The venturi/spray tower and Marble-Bed systems have 20-foot diameter units while the TCA unit is 30 feet in diameter.

The concentration of solids in the underflow of the larger TCA unit has approached the expected final settled concentration of the sludge (approximately 40 wt %). The solids concentration in the underflow streams from the smaller venturi/spray tower and Marble-Bed units, however, has averaged only about 25 wt % indicating they are undersized. To achieve closed liquor loop operation (see Section 10.1), the smaller units had to be used in series with the filter or centrifuge.

10.8.2 Filter

The filter is a Maxibelt rotary drum vacuum filter supplied by Ametek. Some modifications have been made to facilitate trouble free filter cake discharge. Under normal operations, the filter cake contains 50 to 55 and 45 to 50 wt % solids from limestone and lime slurries, respectively.

Filter operation has been significantly hampered by the short life of the filter cloth. The useful life of the polypropylene, nylon, and polyester filter cloths tested, to date, has been generally below 260 hours.

In order to improve cloth life, it is planned in the near future to convert the existing filter to a single roll type with air blowback and scraper discharge.

10.8.3 Centrifuge

The centrifuge is a solid bowl continuous type manufactured by Bird Machine Co. During the limestone reliability verification testing, the centrifuge was used for solids dewatering in the venturi/spray tower and Marble-Bed systems either directly or in series with a clarifier. The cake solids content was satisfactory, at 55 to 65 wt %, and the centrate solids averaged 0.5 to 1.0 wt %. However, a major repair of the unit was necessary after about 1400 hours of operation due to severe erosion.

10.9 LININGS

Two types of lining material were used throughout the scrubber systems. The TCA and Marble-Bed scrubbers, the venturi scrubber downstream of the plug, the spray tower, the process water tanks, most slurry pumps, the circulating slurry piping, and the tank agitator blades were neoprene rubber lined. The effluent hold tanks and clarifiers were glassflake lined.

The rubber linings have been found, generally, to be in excellent condition. Essentially no erosion or deterioration has been noted. However, slight wear was noted on some of the rubber-coated agitator blades. This type of wear is believed to be caused primarily by foreign objects striking the agitator blades (rubber lined pumps are discussed in Section 10.7). One agitator blade neoprene lining was successfully patched with epoxy.

Hairline cracks have been noted on the surface of the glassflake lining of the effluent hold tanks and clarifiers. The cracks did not appear to penetrate the entire thickness of the lining. The cracks were more prevalent at the junction between the baffles and the tank walls. Isolated areas on the bottom of the TCA effluent hold tank also showed wear by erosion. These areas were near the wall baffles where eddy currents are formed.

Glassflake patching material is available for lining repair but has not been used to date. The eroded areas on the bottom of the TCA effluent hold tank were painted with epoxy.

Prior to starting the long term reliability run with limestone on the TCA, the agitator in the effluent hold tank was lowered four feet. As a precautionary measure, a steel wear plate was installed on the bottom of the effluent hold tank, covering the area under the agitator.

10.10 INSTRUMENT OPERATING EXPERIENCE

10.10.1 Sulfur Dioxide Analyzers

Essentially trouble-free operation was experienced with the Du Pont Model 400 UV sulfur dioxide analyzers following the modification of the sampling system and the replacement of interference filters in November 1972. Initially, the sampling system was particularly vulnerable to condensation, solid particulates, oil, soot, corrosion, or the combinations of these factors which led to leakage or plugging of the sampling lines, plugging of the filters, or coating of the optical lens. All of these effects caused erroneous sulfur dioxide analyzer readings.

10.10.2 pH Meters

Two types of pH meters have been used in slurry service: (1) Uniloc Model 320 in-line flow-through meters and (2) Uniloc Model 321 submersible electrode meters.

The performance of the in-line flow-through meters had been unsatisfactory due to the erosion of the glass cells by the slurry, their high rate of failure, and the frequent plugging of the sample lines. All the in-line flow-through meters at the scrubber inlets and outlets have been replaced by the submersible electrode pH meters.

For the submersible electrode pH meters, cell erosion, cell breakage, and sample line plugging has been minimal during the approximately 9000 on-stream hours. Routine cleaning and calibration of the cells that measure the slurry pH at the scrubber inlet are made twice a week to maintain the desired meter accuracy of ± 0.1 pH unit. However, routine calibration checks during the scrubber operation have not been possible for the submersible cells located at the scrubber outlets (inside the downcomers). Studies are being made to effect the routine calibrations of the scrubber outlet pH meters during operation of the scrubber systems.

10.10.3 Density Meters

Operating experience had been gained with three types of density meters in slurry service: (1) Ohmart radiation meters, (2) differential pressure (bubbling tube) meters, and (3) Dynatrol Model CL-10HY vibrating U-tube meters.

Experience with the radiation meter initially indicated a loss of calibration in the range of about 1 to 2 percent per week, but subsequent circuit modification corrected the problem. The meter's accuracy is affected however, by the accumulation of scale on the inner pipe wall at the source probe and unexplained 1-2% instability in periodic cycles.

The sample line and the probes of the differential pressure meter plug frequently and require significant maintenance. However, the meter is accurate when clean and can be used to check the calibration of the Ohmart radiation meters.

The Dynatrol density cells (using the vibration principle of the U-tube for continuous response to a density changes) were installed in September 1973, to measure the densities of the lime slurry feed to the venturi/spray tower system and of the circulating limestone slurry to the TCA system. This meter has also been used to measure limestone feed slurry densities.

The performance of the two installed meters has been excellent with no in-service problems except slugging at low flows (25 percent of design) and loss of accuracy at 150 percent of design flows. The two failures experienced to date resulted from accidents. There has been no indication of any scaling in the sensing tube in either of the three above mentioned services.

10.10.4 Flowmeters

Foxboro magnetic and differential pressure (both orifice and Annubar) flowmeters are used at the test facility.

Operating experience with the magnetic flowmeters has generally been adequate. The main problem has been in obtaining accurate flow measurements at very low flow rates with meters designed to measure flow over a wide range. To assure accuracy, Foxboro recommended a minimum linear velocity of 3 ft/sec through the flow element.

The magnetic flowmeters smaller than 4 inches diameter have a tendency to drift in calibration, and frequent flow checks are required to verify the accuracy. Meters larger than 4 inches are more reliable. However, scale accumulations on the electrodes influence the accuracy and periodic cleaning is necessary.

The orifice flowmeters function well in slurry service (6 to 15 percent solids by weight), provided that pressure taps are protected from plugging by using diaphragms as close as possible to the slurry piping. Inspection results of 304 and 316 stainless steel orifice plates indicate little erosion after 7500 and 4500 hours of service, respectively. Estimated error in flow measurement due to erosion was less than 5 percent.

Experience at the test facility indicates that Annubar meters should be used only in non-scaling, clear liquid service (containing a maximum of 0.5 percent by weight of suspended solids) to prevent frequent plugging and associated maintenance work.

10.10.5 Control Valves

Operating experience with control valves in slurry service has generally been unsatisfactory. Severe erosion in a short time is caused by the increased velocity during throttling operation. This deterioration has been observed in stainless steel plug valves, globe valves, and rubber pinch valves. Satisfactory and trouble free flow control has been experienced only with variable speed pumps.

10.11 MATERIALS EVALUATION

TVA has conducted a study for the evaluation of corrosion and wear of plant equipment and test specimens (coupons) at the Shawnee facility. Two interim reports on the results of this study have been written by G. L. Crow and H. R. Horsman. The first interim report is presented in Appendix J and summarized in this section. The second interim report was received only in time to include it in Appendix K. Linings have been previously discussed in Section 10.9.

10.11.1 System Components

A thorough inspection of all system components was conducted during the extended February and March 1973 boiler outage. Each of the three scrubber systems had been operated for about 1800 hours during the limestone factorial tests.

Localized deposits of loose fly ash accumulated in the gas ducts between the boiler and scrubber structure. The surfaces of the mild steel ducts were coated with a thin iron oxide scale. Moderate pitting had occurred at the uninsulated connections apparently due to local condensation. The flanges and access doors have since been insulated to avoid this problem.

The most severe corrosion was found on Type 316 stainless steel surfaces, particularly on the mist eliminator blades in the TCA system. In general, the corrosion was in the form of pitting with some pits as large as 1/16-inch diameter and 30 to 35 mils deep.

Significant erosion was noted on the pump sleeves, at the intersections of the wire of support grids in the TCA scrubber, and on the impeller and casing of the 316 SS Gould limestone slurry pump.

10.11.2 Test Coupons

Test coupons of several different materials of construction, together with stressed and welded specimens, were exposed for periods of 1700 hours or longer to various slurry and gas environments. The corrosion rates observed are presented in Table 10-1.

With few exceptions, mainly in the TCA system, the greatest loss of weight from metal specimens occurred in areas where the velocity of the unscrubbed, partially humidified flue gas was comparatively high. Impingement on the specimens of the slurry caused erosion and corrosion. Pitting and crevice corrosion were not important factors where erosion and corrosion kept the specimens clean. In other areas of the three scrubber systems where solids accumulated,

Table 10-1

CORROSION TEST RESULTS

Metals [a]	Corrosion, mils/yr	Number of Pitted Samples[b]	Pitted Depth, [c] mils		Number of Samples With Crevice Attack	Other Types of Attack	
			Min.	Max.		Number of Samples[b]	Area of Attack
1. Hastelloy C-276	Neg. to 5	-	-	-	-	-	-
2. Inconel 625	Neg. to 3	1	-	Minute	-	-	-
3. Incoloy 825	Neg. to 7	-	-	-	1	-	-
4. Carpenter 20Cb-3	Neg. to 14	2	-	Minute	-	-	-
5. Type 316L SS	Neg. to 15	3	-	Minute	2	1,1	(d) G18, Weld
6. Cupro-Nickel 70-30	>1 to 49	1	-	18	-	1	Weld
7. Monel 400	>1 to 57	1	-	2	1	1	Weld
8. Hastelloy B	>1 to 100	2	-	Minute	-	-	-
9. Type 446 SS	Neg. to <140	9	Minute	19	11	-	-
10. E-Brite 26-1	Neg. to <190	10	Minute	18	2	-	-
11. Incoloy 800	Neg. to <190	6	Minute	19	3	1	(e)
12. USS 18-18-2	Neg. to <200	11	Minute	16	11	-	-
13. Type 304L SS	Neg. to <200	14	Minute	25	11	1	(e)
14. Type 410 SS	>1 to <250	15	Minute	16	16	-	-
15. Aluminum 3003	>1 to <500	3	2	70	5	-	-
16. Mild Steel A-283	>1 to <1400	2	-	Minute	3	-	-
17. Cor-Ten B	>1 to <1400	5	Minute	9	4	1	Weld

Non-Metals[f]		Evaluation, Number of Samples		
		Good	Fair	Poor
Plastics	Bondstrand 4000	12	-	9
	Flakeline 200	2	14	5
	Qua-Corr	7	-	1
Rubbers	Butyl 1175	8	-	-
	Natural 9150	8	-	-
	Neoprene 26,000	8	-	-
Ceramic	Transite	14	2	5

Note: Test samples of each material were tested for 1140 hours, or more.

(a) Metals are listed in approximate order of decreasing corrosion resistance.
(b) Samples of each metal were tested in 21 locations.
(c) Depth of penetration in mils during total exposure period.
(d) Groove in parent metal is 18 mils deep.
(e) Severe localized attack of parent metal.
(f) Samples of Bondstrand, Flakeline and Transite were tested in 21 locations. Samples of Qua-Corr and rubbers were tested in 8 locations.

the frequency of localized corrosion was high. However, each of the 17 alloys tested showed good corrosion resistance at one or more test locations in each scrubber system.

Corrosion of Hastelloy C-276 was from negligible to 5 mils per year. This alloy showed no evidence of localized attack in any test location. Next in resistance to corrosion were Inconel 625, Incoloy 825, Carpenter 20 Cb-3, and Type 316L stainless steel alloys. The corrosion rates for each material ranged from negligible to 5, 7, 14, and 15 mils per year, respectively. These alloys had few minute corrosion pits and/or crevice corrosion. Type 316L, the fifth alloy in corrosion resistence, is the least expensive of this group of materials.

Three nonferrous alloys, Cupro-Nickel 70-30, Monel 400, and Hastelloy B, each had minimum corrosion rates of less than 1 mil. Maximum corrosion rates were 49, 57, and 100 mils per year, respectively. Only one or two specimens pitted. In three tests of Monel and in one test of Cupro-Nickel 70-30, the welds were inferior to the parent metal.

The corrosion rates of Type 446 stainless steel, E-Brite 26-1, Incoloy 800, USS 18-18-2, and Type 304L stainless steel ranged from negligible to values which indicated that the alloy specimen was completely destroyed at one or more test locations. The values for the specimen failures ranged from greater than 140 mils per year for Type 446 to greater than 200 mils for both USS 18-18-2 and Type 304L stainless steels. These five alloys were highly susceptible to localized corrosion.

Another group of alloys, Type 410 stainless steel, 3003 aluminum, A-283 mild steel, and Cor-Ten B, had minimum corrosion rates of less than 1 mil per year and maximum corrosion rates of greater than 250 mils for Type 410 to greater than 1400 mils for A-283 and Cor-Ten B. Pitting and crevice corrosion occurred on the four alloys.

In general, the stressed specimens (five alloys only) were not corroded at rates higher than their counterpart disk-type specimens.

Specimens of Bondstrand 4000, Flakeline 200, and Transite materials were tested at 21 locations. Bondstrand 4000 showed good corrosion resistance in 12 tests and poor resistance in nine tests. Only six specimens of each of the following materials were tested: Qua-Corr plastic, butyl natural rubber, and neoprene rubber. The results showed five good specimens and one poor specimen for Qua-Corr plastic, and six good specimens for each type rubber.

Section 11

PARTICULATE REMOVAL TEST RESULTS

Overall particulate removal tests were conducted by the EPA on all three scrubber systems during the limestone factorial testing (November 1972 to January 1973). Results of these tests are presented in Tables 11-1 through 11-3. During the limestone reliability verification testing (May 1973), the EPA conducted both overall particulate removal tests and particulate distribution tests on the TCA. These results are presented in Table 11-4 and Figures 11-1 and 11-2. Results of overall particulate removal measurements taken by TVA personnel at various times (May through October 1974) during reliability testing are presented in Tables 11-5 and 11-6 for the venturi/spray tower and the TCA system, respectively.

11.1 OVERALL PARTICULATE REMOVAL EFFICIENCIES

To obtain overall particulate removal efficiencies in the three scrubber systems, a modified EPA particulate train (manufactured by Aerotherm/Acurex Corporation) was used to measure mass loading at the scrubber inlets and outlets. Only those data which were taken at close-to-isokinetic sampling conditions are reported here. All of the outlet particulate data obtained prior to the modification of the reheaters during the 1973 boiler outage have been corrected for

Table 11-1

OVERALL PARTICULATE REMOVAL IN VENTURI/SPRAY TOWER DURING LIMESTONE FACTORIAL TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm		Pressure Drop, in. H_2O		Grain Loading, grains/scf		Percent Removal
			Venturi	Spray Tower	Venturi	Spray Tower[(a)]	Inlet	Outlet	
415-1A	11/09/72	23,800	305	0	9.0	2.0	4.38	0.012	99.7
414-1D	11/12/72	23,800	305	0	9.0	1.9	2.1	0.010	99.5
414-1D	11/14/72	23,700	305	0	9.0	1.9	3.32	0.013	99.6
414-1C	11/15/72	23,700	305	0	6.4	1.9	3.40	0.02	99.4
417-1A	12/22/72	23,800	605	0	9.5	1.9	3.38	0.012	99.6
414-1E	12/25/72	23,800	300	0	12.0	1.9	4.17	0.009	99.8
418-1C	12/27/72	11,800	600	0	12.5	0.4	6.39	0.114	98.2
453-1B	12/31/72	11,800	12	460	2.5	0.45	2.6	0.004	99.8
454-1B	1/04/73	11,800	12	450	0.75	0.45	4.62	0.07	98.5
456-1A	1/05/73	11,800	12	450	0.70	0.45	3.38	0.056	98.3

(a) Including mist eliminator.

Table 11-2

OVERALL PARTICULATE REMOVAL IN TCA SCRUBBER WITH FIVE GRIDS AND NO SPHERES DURING LIMESTONE FACTORIAL TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm	Total Pressure Drop, in. H_2O	Grain Loading, grains/scf		Percent Removal
					Inlet	Outlet	
WC-5	12/21/72	15,800	730	3.8	1.70	0.004	99.8
WC-5A	1/06/73	15,900	730	4.7[(a)]	4.16	0.029	99.3
WC-5A	1/09/73	15,900	730	5.5[(a)]	1.32	0.019	98.6
WC-11	1/12/73	16,000	745	7.0[(a)]	3.29	0.017	99.5
WC-12	1/14/73	15,900	375	7.1[(a)]	3.65	0.022	99.4

(a) High total pressure drop (including Koch tray, mist eliminator, and inlet duct) due to plugging of the inlet gas duct by solids deposit.

Table 11-3

OVERALL PARTICULATE REMOVAL IN MARBLE-BED SCRUBBER DURING LIMESTONE FACTORIAL TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm	Total Pressure Drop, in. H_2O	Grain Loading, grains/scf		Percent Removal
					Inlet	Outlet	
427-3A	11/13/72	15,800	810	12.2	2.6	0.030	98.8
427-3A	11/16/72	15,800	810	12.2	3.32	0.035	98.9
426-3B	11/28/72	15,800	810	10.2	4.43	0.032	99.3
427-3C	12/02/72	15,800	800	12.7	4.24	0.033	99.2
427-3B	12/24/72	15,800	805	11.2	2.19	0.027	98.8
428-3A	12/28/72	15,800	810	11.7	3.78	0.025	99.3
428-3A	12/29/72	15,800	810	11.7	4.12	0.016	99.6
428-3A	12/30/72	15,800	810	11.7	3.63	0.035	99.0
438-3A	1/07/73	15,800	400	7.2	4.20	0.020	99.5
440-3A	1/11/73	9,900	600	6.9	3.82	0.042	98.9
440-3A	1/13/73	9,900	600	6.9	3.59	0.066	98.2

Table 11-4

OVERALL PARTICULATE REMOVAL IN TCA SCRUBBER
DURING LIMESTONE RELIABILITY VERIFICATION TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm	Pressure Drop,[a] in. H_2O	Grain Loading, grains/scf		Percent Removal
					Inlet	Outlet	
503-2A	5/22/73	20,600	1200	9.8	3.16	0.00852	99.7
					3.00	0.00375	99.9
506-2A	5/24/73	16,500	1200	7.5	2.89	0.0143	99.5
					2.13	0.0152	99.3
505-2A	5/23/73	16,500	600	5.6	2.34	0.031	98.7
					2.61	0.020	99.2
					2.28	0.010	99.6

(a) For a TCA with 3 beds, 5 in. spheres/bed and including mist eliminator and Koch tray.

Table 11-5

OVERALL PARTICULATE REMOVAL IN VENTURI/SPRAY TOWER DURING LIME RELIABILITY TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm		Pressure Drop, in. H_2O		Grain Loading, grains/scf		Percent Removal
			Venturi	Spray Tower	Venturi	Spray Tower[(a)]	Inlet	Outlet	
604-1A	6/26/74	19,800	100	1200	1.9	3.0	2.52	0.024	99.1
608-1A	9/11/74	19,800	600	1200	9.0	2.2	2.28	0.023	99.0
610-1A	10/10/74	19,800	600	1200	9.0	3.2	2.72	0.021	99.2

(a) Including mist eliminator.

Table 11-6

OVERALL PARTICULATE REMOVAL IN TCA SCRUBBER DURING LIMESTONE RELIABILITY TESTS

Run No.	Date	Gas Rate, acfm (sat.) @ 125°F	Liquor Rate, gpm	Pressure Drop,(a) in. H_2O	Grain Loading, grains/scf		Percent Removal
					Inlet	Outlet	
531-2A	5/15/74	16,900	1200	6.7	2.82	0.029	99.0
531-2A	6/12/74	16,900	1200	10.0	3.47	0.010	99.7
532-2A	7/24/74	16,900	1700	6.7	3.33	0.024	99.3
535-2A	9/27/74	16,900	1200	6.2	2.73	0.016	99.4
535-2A	10/30/74	16,900	1200	6.2	2.24	0.023	99.0

(a) For a TCA with 3 beds, 5 in. spheres/bed and including mist eliminator and Koch tray.

soot-contamination from the flue gas reheaters.* The soot amounted to less than 30 percent of the total mass of the outlet particulates.

The overall particulate removal efficiencies measured in the three scrubber systems appear to be higher than the efficiencies predicted from "impaction theory". These improved efficiencies could be due to condensation of water vapor in the flue gas on the solid particles.** In order to verify the particulate removal results obtained, to date, and identify the causes for the observed removals, EPA has planned a new test series for the determination of size and overall removal efficiencies in the TCA and venturi/spray tower systems.

11.1.1 Venturi/Spray Tower System

Results of tests conducted on the venturi/spray tower system by the EPA during limestone factorial testing are presented in Table 11-1. Tests were conducted with slurry to the Chemico venturi only (Runs 415-1A through 418-1C) and with slurry primarily to the spray tower (Runs 453-1B through 456-1A). Overall particulate removal efficiencies of 99.4 to 99.8 percent*** were obtained for the venturi at a gas flow rate of 24,000 acfm (125°F), liquid-to-gas ratios from 12.5 to 25 gal/

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*See Section 10.5 for a discussion of soot contamination from the oil-fired reheaters.

**The condensation of water vapor per unit mass of inlet solids has been estimated to be from 1 to 5 grains water/grain inlet particulates within the scrubber.

***For an average scrubber inlet grain loading of 3.5 grains/scf, a particulate removal of 99.0 percent would correspond to 0.07 lbs particulate discharged per 10^6 Btu.

mcf (300-600 gpm), and venturi plug pressure drops from 6 to 12 inches H_2O. For the spray tower, the removal efficiency was about 98.5 percent at a gas velocity of 4 ft/sec and a liquid-to-gas ratio of 37 gal/mcf (12,000 acfm and 450 gpm).

Particulate removal tests by TVA during lime reliability testing were made with the venturi and spray tower operating simultaneously. These are reported in Table 11-5. Overall particulate removal efficiencies of 99.0 to 99.2 percent were obtained with a gas flow rate of 20,000 acfm (125°F), venturi pressure drops from 2 to 9 inches H_2O, and liquid-to-gas ratios of 5 to 30 gal/mcf and 61 gal/mcf for the venturi and spray tower, respectively.

11.1.2 TCA System

The EPA measurements during limestone factorial testing on the TCA scrubber with 5 grids and no spheres are presented in Table 11-2. Overall removal efficiencies were 98.6 to 99.8 percent at a gas velocity of 8 ft/sec and a liquid-to-gas ratio of 46 gal/mcf (16,000 acfm and 730 gpm), with total pressure drops (including Koch tray, mist eliminator, and inlet duct) of 4 to 7 inches H_2O.

Further measurements by the EPA during limestone reliability verification testing on the TCA scrubber with 3 beds and 5 inches of spheres per bed are presented in Table 11-4. Overall removal efficiencies of 98.7 to 99.9 percent were achieved at gas velocities from 8.4 to 10.4 ft/sec (16,500 to 20,600 acfm), liquid-to-gas ratios from 37 to 75 gal/mcf (600-1200 gpm), and total pressure drops from 5.5 to 10 inches H_2O. The higher pressure drops generally gave higher overall removal efficiencies.

TVA measurements during limestone reliability tests on the TCA scrubber, again with 3 beds and 5 inches of spheres per bed, are presented in Table 11-6. Removal efficiencies were all greater than 99 percent. These data are in substantial agreement with the EPA measurements.

11.1.3 Marble-Bed System

Measurements by EPA on the Marble-Bed scrubber during limestone factorial testing are presented in Table 11-3. The Marble-Bed scrubber gave an overall particulate removal efficiency range of 98.8 to 99.6 percent at a gas velocity of 5.5 ft/sec, a liquid-to-gas ratio of 51 gal/mcf (15,800 acfm and 810 gpm), and 12 inches H_2O total pressure drop.

11.2 PARTICULATE REMOVAL AS A FUNCTION OF PARTICLE SIZE

During the limestone reliability verification testing, a special series of tests using a Brink impactor were conducted by EPA to measure the TCA inlet and outlet aerodynamic size distributions. In order to utilize the Brink impactor at scrubber inlet mass loading conditions, a modified EPA particulate mass sampling train was used. The train was of 316 stainless steel construction and consisted mainly of a heated sample probe (6 feet x 1/2 inch outside diameter), a cyclone, and the Brink impactor with a 144 mm glass fiber filter. The impactor drew a sample from the gas stream exiting the cyclone. Previous work elsewhere by the EPA had established that the particles collected in the cyclone had a mass mean diameter of approximately 5 microns at a flow rate of one cubic foot per minute. At the scrubber outlet, the Brink impactor was used directly in the flue gas duct (without sample probe and cyclone).

11.2.1 Particulate Size Distribution in the TCA

The particulate size distributions at the TCA inlet and outlet were measured by the EPA for the runs listed in Table 11-4. The results are plotted in Figure 11-1 as cumulative weight percent versus particle size.

As shown in Figure 11-1, the mass mean diameter of the inlet solids was approximately 23 microns, which is slightly greater than the "normal" range of 10 to 20 microns. The data for the outlet size distribution shows some scatter. The mass mean diameter ranged from about 0.5 to 0.75 micron for a total pressure drop range of 5.5 to 10.0 inches H_2O. Generally, the higher pressure drops give smaller outlet mass mean diameters.

11.2.2 Particulate Removal Efficiency in the TCA as a Function of Particle Size

Based on the measured particulate size distributions, the particulate removal efficiency as a function of particle size was determined by EPA for the TCA runs shown in Table 11-4. In Figure 11-2 the percent penetration (100 minus percent removal) is plotted versus particle diameter in microns for different ranges of total pressure drop.

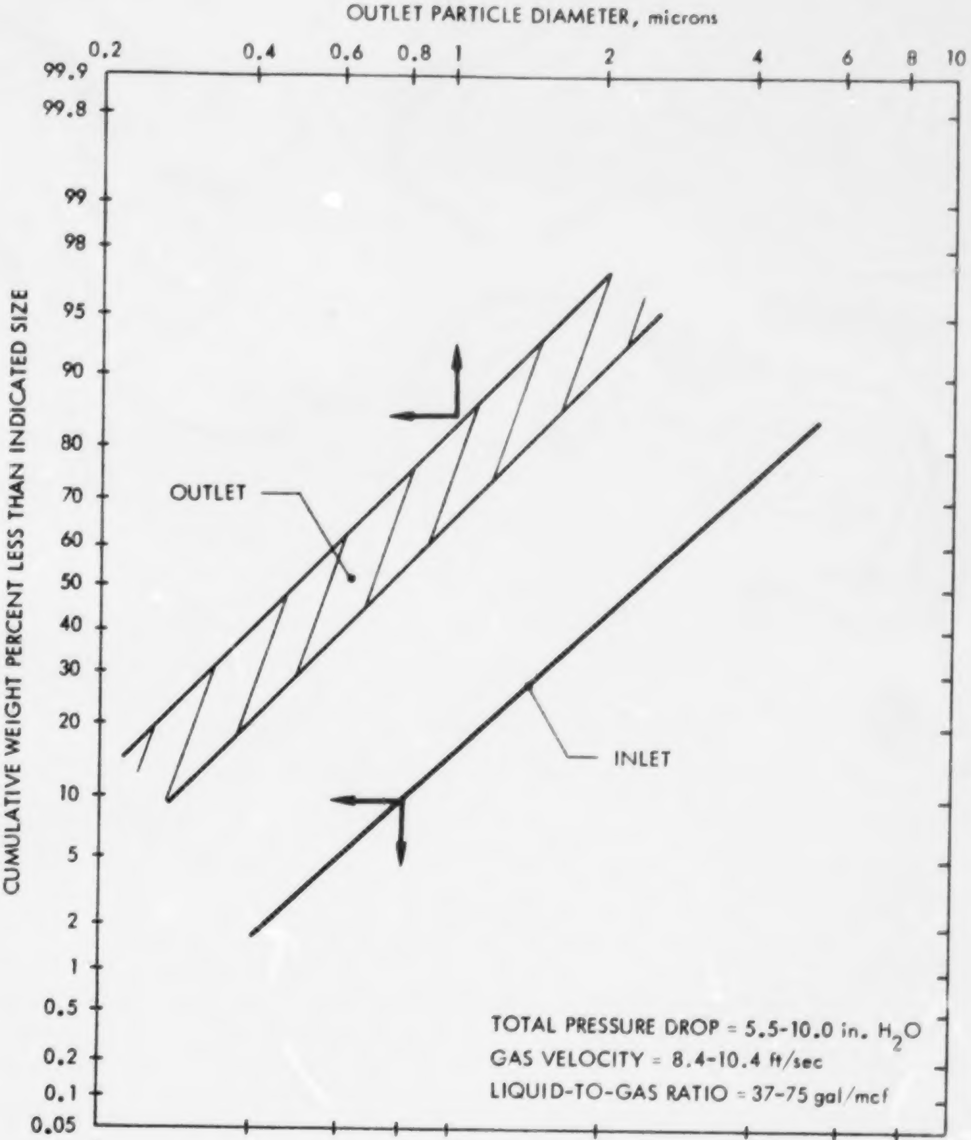

Figure 11-1. Particle Size Distributions at TCA Inlet and Outlet

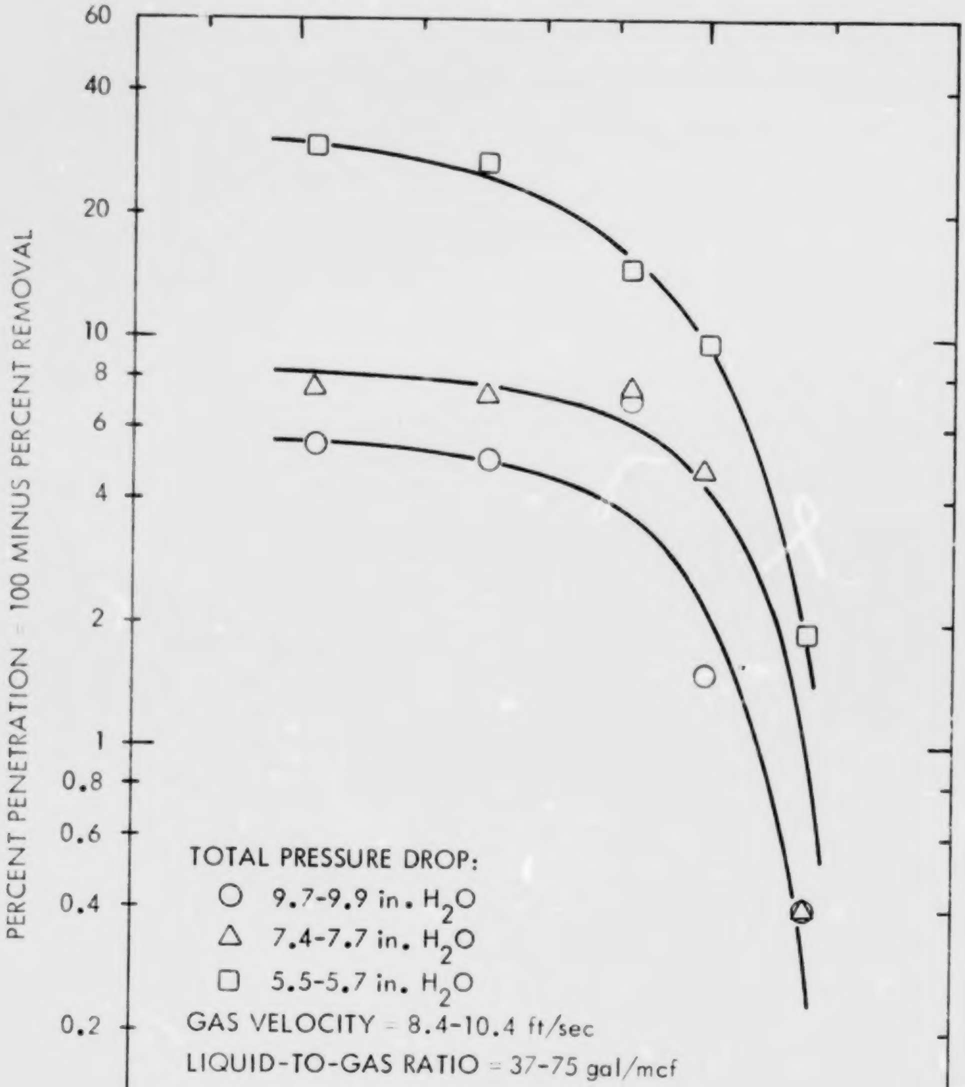

Figure 11-2. TCA Particulate Removal Efficiency as a Function of Particle Size

As seen in Figure 11-2, the removal efficiency dropped rapidly with decreasing particle diameter down to about 0.5 micron and then leveled off over the range of 0.5 micron to 0.1 micron. For the submicron particles (0.1 to 1.0 micron), the removal efficiency dropped rapidly with decreasing pressure drop. The efficiencies were 94 to 98 percent at 9.8 inches H_2O total pressure drop, 92 to 95 percent at 7.6 inches H_2O, and 71 to 90 percent at 5.6 inches H_2O. Because of the limited number of tests, conclusions regarding submicron collection efficiency should be reserved until additional testing can be carried out.

Section 12

ANALYSIS OF PRESSURE DROP DATA

In this section theoretical equations were fitted to the pressure drop data obtained during air/water and sodium carbonate testing (see Section 5) for each of the three scrubbers.

12.1 VENTURI SCRUBBER

In Reference 6 a proposed correlation was presented for fitting venturi pressure drop.* A further analysis of the differential equations which describe pressure drop for a venturi (see Reference 13) indicated that the ratio of throat length to plug diameter, ℓ/D, should be included in the expression.** The inclusion results in a much improved fit to the data, especially at high gas velocities and high liquid-to-gas ratios.

The following equation is a fit to the venturi air/water and soda-ash pressure drop data (see Section 5.1.1 and Appendix D, Tables D-1, D-2, and D-3):

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*The proposed correlation (Equation 3 of Reference 6) should have shown the coefficient β_3 multiplied by v_t^2.

**Volgin (Reference 14) included a "throat length" term in his venturi pressure drop correlation but gave no theoretical grounds for the inclusion.

$$\Delta p = 2.8 \times 10^{-4} v_t^{2} + 7.5 \times 10^{-5} v_t^{2.38} (L/G)^{0.897} (\ell/D)^{1.68} \qquad (12\text{-}1)$$

with:

$$\ell = 0.56 + 0.009\,(\%\text{ opening of plug}) \qquad (12\text{-}2)$$

$$A_t = 1.5 + 0.0048\,(\%\text{ opening of plug}) \qquad (12\text{-}3)$$

where:

Δp = pressure drop across venturi, in. H_2O
v_t = gas velocity at throat, ft/sec
L/G = liquid-to-gas ratio through scrubber, gal/mcf
ℓ = throat length, ft
D = venturi plug diameter = 3.2 ft for the Chemico venturi
A_t = venturi throat area (used to calculate gas velocity), ft^2

The preconstant in the first term on the right-hand side of Equation 12-1 was fitted to the "air only" (L=0) data. The four coefficients in the second term on the right-hand side were fitted to the remaining data.

Equation 12-1 accounts for 97 percent of the variation of the air/water and soda-ash data with a standard error estimate of 0.7 inch H_2O.* Measured and predicted (Equation 12-1) values of venturi pressure drop are compared in Figure 12-1. Also shown

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* See Appendix L for definition of statistical terms.

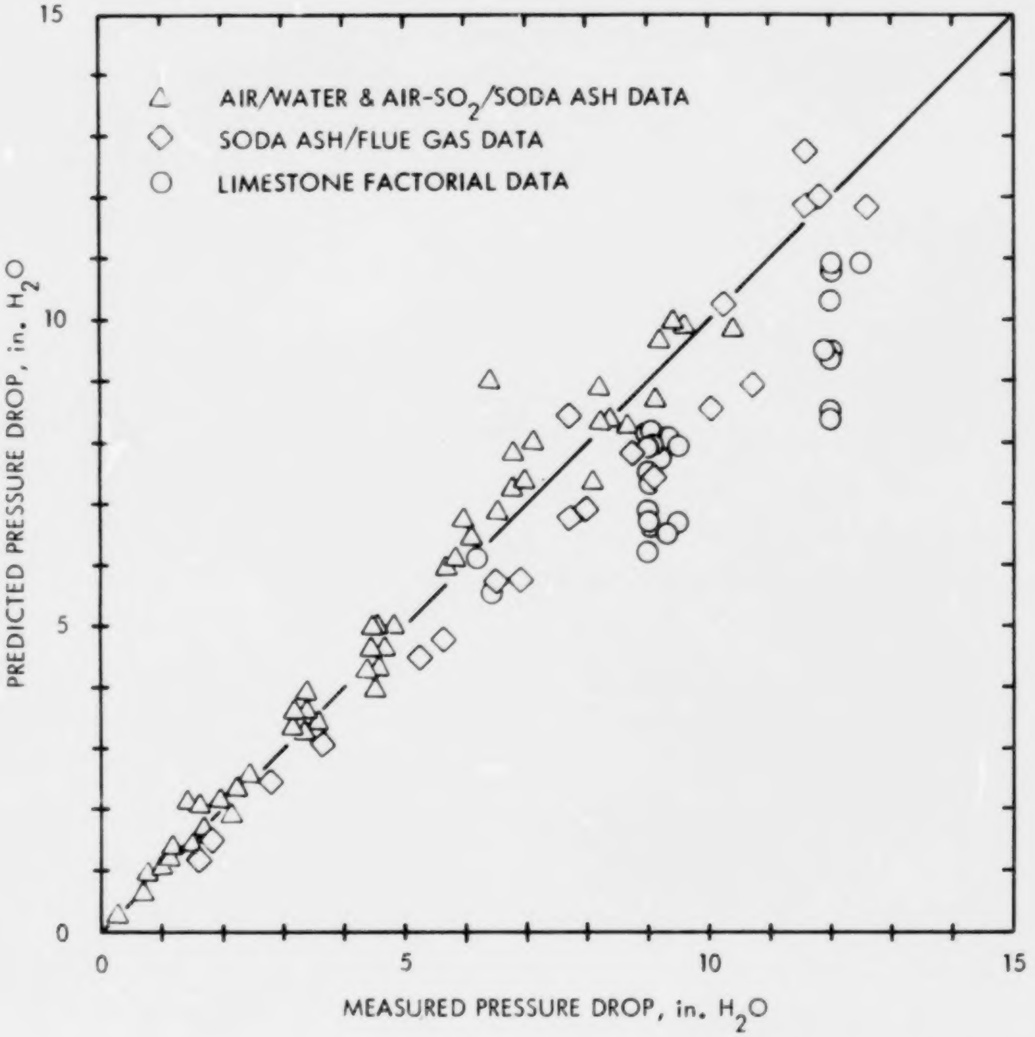

Figure 12-1. Comparison of Experimental Data and Predicted Values of Pressure Drop in the Chemico Venturi from Equation 12-1

in Figure 12-1, but not included in the fit of Equation 12-1, is the pressure drop data for the limestone factorial runs (see Appendix E, Table E-1).

The four coefficients in the second term on the right-hand side of Equation 12-1 were also fitted to the limestone factorial data. The resultant equation is:

$$\Delta p = 2.8 \times 10^{-4} v_t^{2} + 10.0 \times 10^{-5} v_t^{-2.46} (L/G)^{0.62} (\ell/D)^{1.36} \qquad (12\text{-}4)$$

The equation accounts for 92 percent of the variation of the data. Measured and predicted values of pressure drop are compared in Figure 12-2.

12.2 TCA SCRUBBER

The following equation was fitted to the TCA pressure drop data for the air/water and soda-ash runs (see Section 5.1.2 and Appendix D, Tables D-4, D-5, and D-6) and for the limestone factorial runs (see Appendix E, Table E-2):*

$$\Delta p = 1.2 + 6.3 \times 10^{-5} v^{2} (L/G) \left[h_p / d_p + N_S \right] \qquad (12\text{-}5)$$

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*Thirteen runs were eliminated from this analysis. These included nine TVA grid-tower runs for which the inlet gas duct was partially plugged and four runs operated under "flooding" conditions.

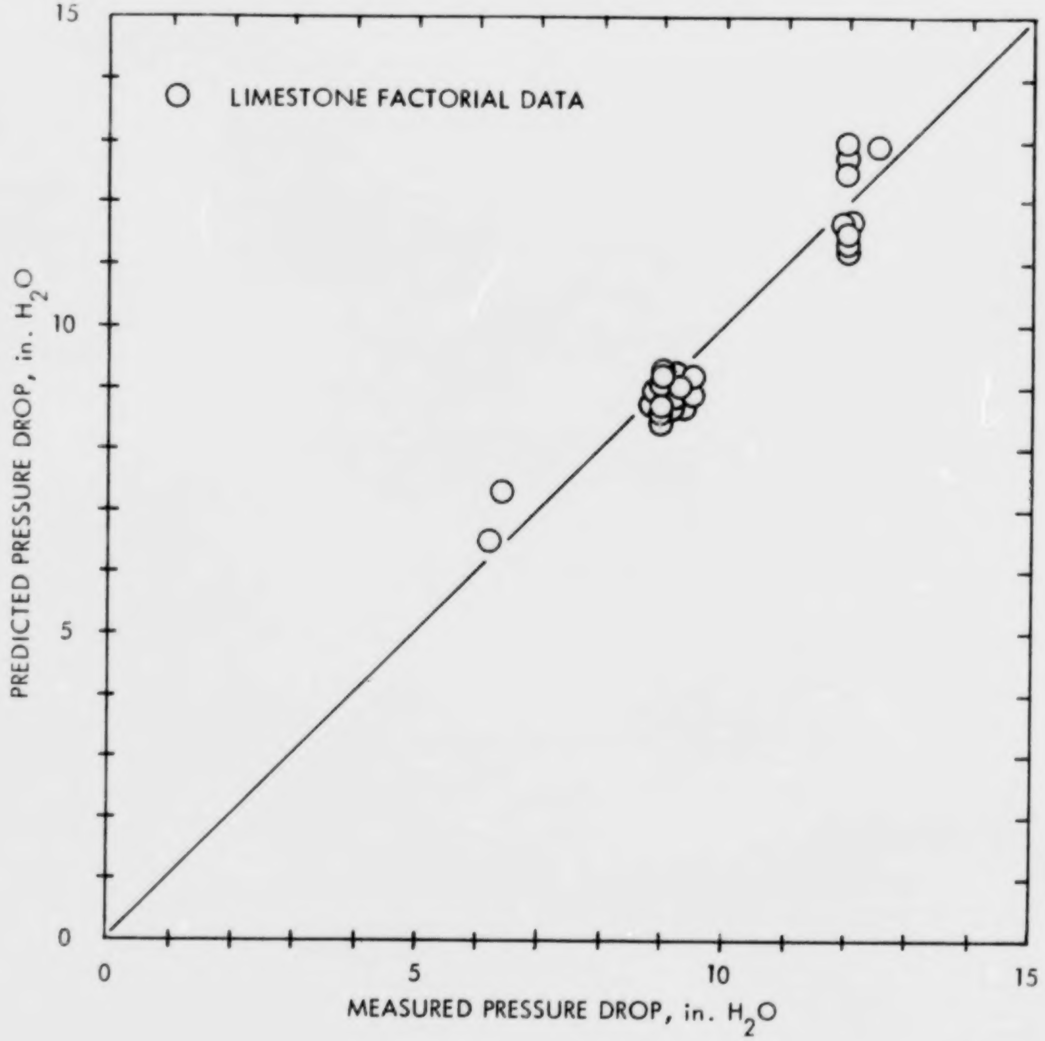

Figure 12-2. Comparison of Experimental Data and Predicted Values of Pressure Drop in the Chemico Venturi from Equation 12-4

where:

Δp	pressure drop across TCA (excluding mist eliminator), in. H_2O
v	gas velocity through scrubber, ft/sec
L/G	liquid-to-gas ratio through scrubber, gal/mcf
h_p	total height of packing, in.
d_p	diameter of packing = 1.5 in.
N_s	number of grids (screens)

The data fitted to this equation were taken with wire mesh grids which were subsequently replaced with bar-grids. Pressure drop across bar-grids is slightly lower.

Equation 12-5 gives the best least-squares fit not only for the combined air/water, soda-ash, and limestone data but also for the limestone data alone. The equation accounts for 91 percent of the variation of the combined data and for 94 percent of the variation of the limestone data. Standard errors of estimate are 0.70 inch H_2O overall and 0.62 inch H_2O for the limestone data. Measured and predicted values of pressure drop are compared in Figure 12-3.

The pre-constant of 1.2 inches H_2O on the righthand side of Equation 12-5 represents the average pressure drop for the TCA system when operated as a "spray tower" (no grids or spheres). The second term on the right-hand side represents the pressure drop across the TCA bed of spheres. The form for this expression was obtained from the work of Happel (Reference 15) and Leva (Reference 16) for pressure drop through a two-phase fluidized bed at high Reynolds numbers.[*]

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[*] Reynolds number = $\frac{\text{(plastic sphere diameter)(gas velocity)(gas density)}}{\text{(gas viscosity)}}$

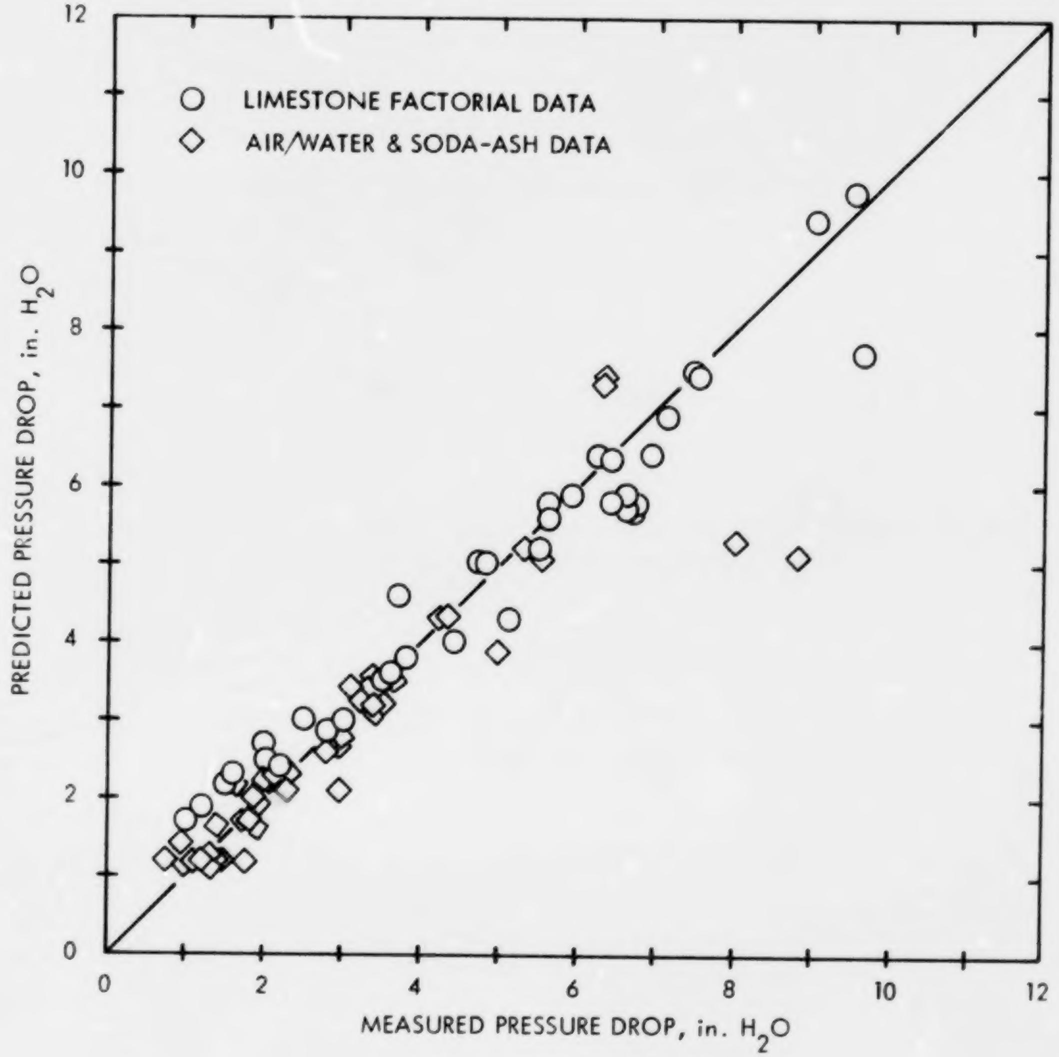

Figure 12-3. Comparison of Experimental Data and Predicted Values of Pressure Drop in the TCA from Equation 12-5

12.3 MARBLE-BED SCRUBBER

The following equation was fitted* to the Marble-Bed pressure drop data for the air/water and soda-ash runs (see Appendix D, Tables D-7, D-8, and D-9):

$$\Delta p = 0.056\, v^{2} + 0.016\, (L/G)^{0.67}\, v^{1.14}\, (h_M/d_M) \qquad (12\text{-}6)$$

where:

Δp = pressure drop across Marble-Bed (excluding mist eliminator), in. H_2O

v = gas velocity through scrubber, ft/sec

L/G = liquid-to-gas ratio through scrubber, gal/mcf

h_M = height of marbles, in.

d_M = marble diameter = 0.75 in.

Equation 12-6 accounts for 86 percent of the total variation of the data with a standard error of estimate of 1.2 inches H_2O. Further attempts to improve the fit of the equation by including other variables, such as height of turbulent layer, were unsuccessful.

Measured and predicted values of Marble-Bed pressure drop for Equation 12-6 are compared in Figure 12-4.

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*The pre-constant in the first term on the righthand side of Equation 12-6 was fitted to the "air only" (L=0) data. The three coefficients in the second term on the righthand side were fitted by least squares to the remaining data.

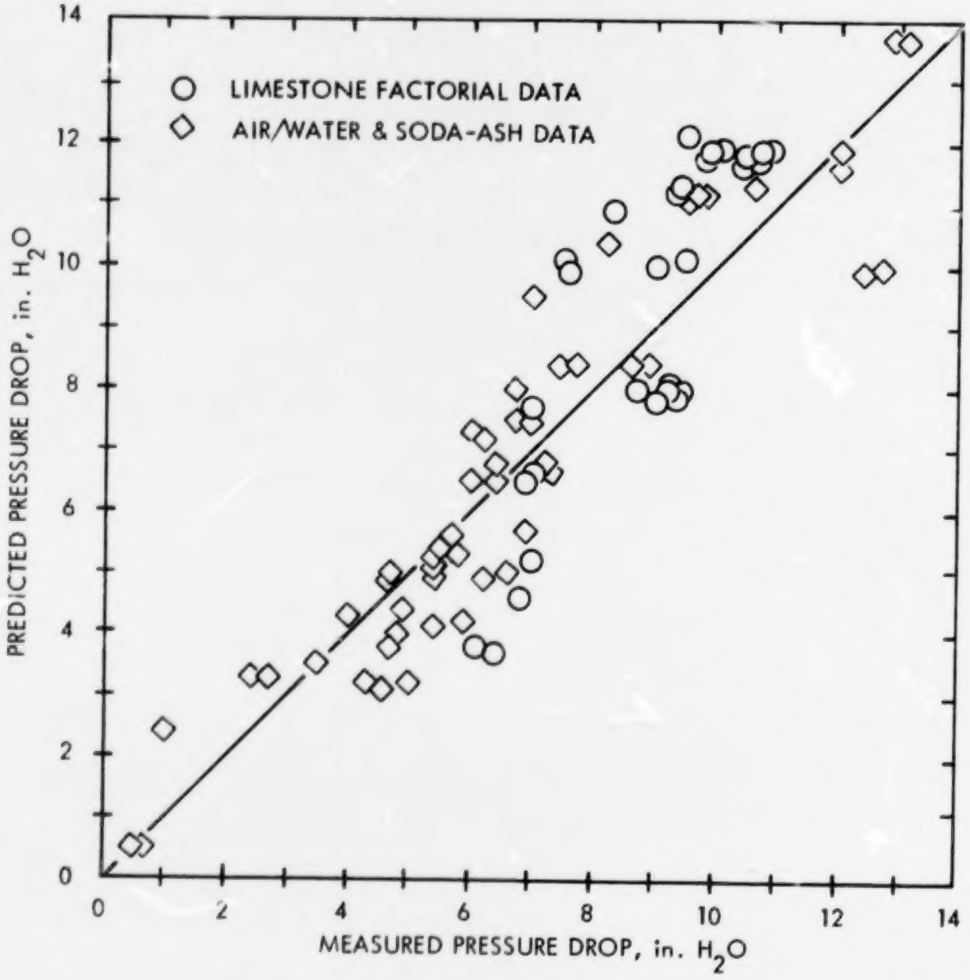

Figure 12-4. Comparison of Experimental Data and Predicted Values of Pressure Drop in the Marble-Bed Scrubber from Equation 12-6

Also shown in Figure 12-4, but not included in the fit of Equation 12-6, is the pressure drop data for the limestone factorial runs presented in Table E-3 of Appendix E. The equation is not a good representation of the limestone data, perhaps due to an effect of percent solids in the slurry and due to the gradual plugging of the marble bed during many of the test runs (several runs whose pressure drops clearly indicated plugging were omitted from the analysis).

The following equation, based on the form of Equation 12-6, was fitted to the data from the limestone factorial runs:

$$\Delta p = 5.1 + 0.0079\, v^{1.14} (L/G)^{0.67} (h_M/d_M) \qquad (12\text{-}7)$$

Equation 12-7 accounts for 75 percent of the total variation of the data with a standard error of estimate of 0.8 inch H_2O. The equation does not hold for pressure drops less than six inches H_2O.

Measured and predicted values of Marble-Bed pressure drop for Equation 12-7 are compared in Figure 12-5.

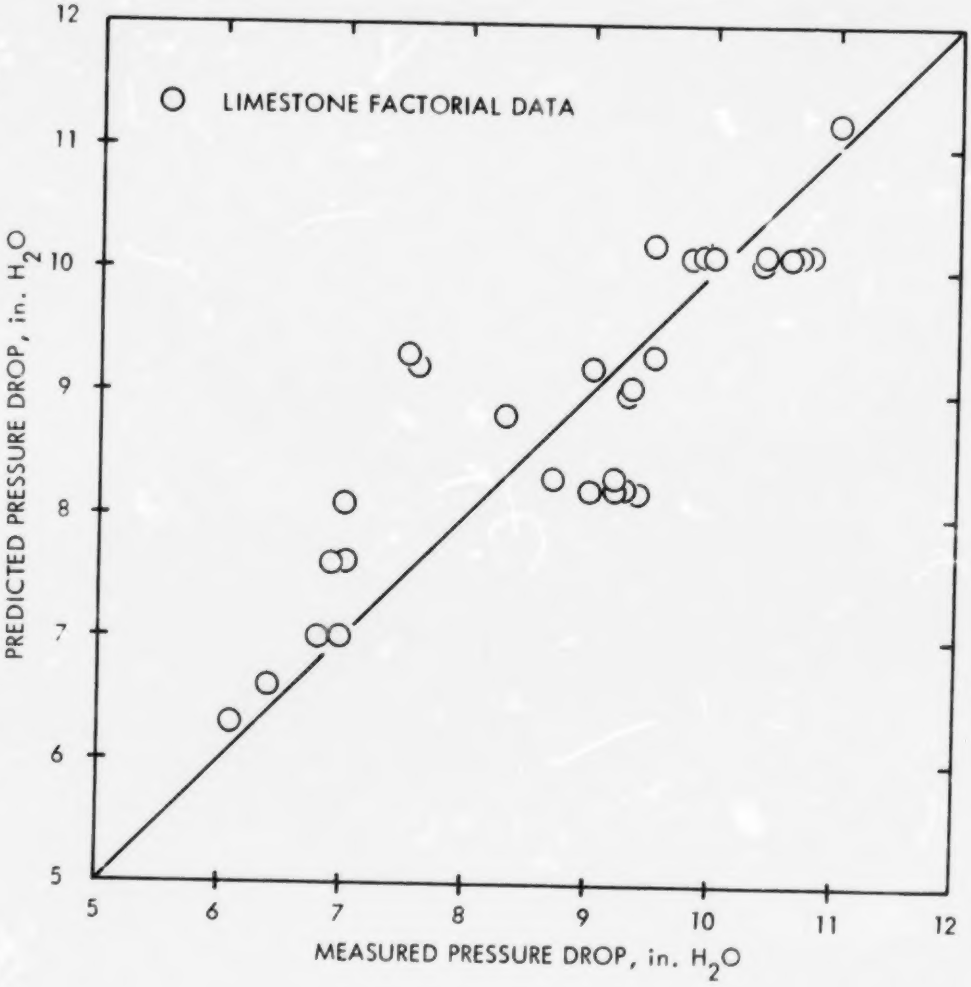

Figure 12-5. Comparison of Experimental Data and Predicted Values of Pressure Drop in the Marble-Bed Scrubber from Equation 12-7

Section 13

ANALYSIS OF SODIUM CARBONATE SCRUBBING DATA

In this section, the sodium carbonate (soda-ash) data are analyzed and models are presented for predicting SO_2 removal in sodium carbonate systems. In Section 13.1, models are fitted to the "gas-side resistance" data where the gas-side mass transfer resistance is controlling. Equations are presented for predicting SO_2 removal in (1) the Chemico venturi, (2) the TCA operated as a one-stage spray tower, and (3) the Marble-Bed absorber. In Section 13.2, a model is fitted to the "gas/liquid-side resistance" data where both gas-side and liquid-side mass transfer resistances are significant. An equation is presented for predicting SO_2 removal under such conditions in the Chemico venturi. It should be noted that none of these correlating equations are useful for lime/limestone scrubbing systems where gas-side resistance is negligible and where the dependence of the controlling liquid-side resistance on the operating variables differs from a soda-ash system.

13.1 GAS-SIDE RESISTANCE DATA

As mentioned previously, the gas-side resistance tests were designed, primarily, to determine uncertain coefficients in models where gas-side mass transfer is rate controlling. For gas-side controlling mass transfer, the absorption efficiency is independent of both liquor composition and inlet gas concentration of the absorbed component.[*] Data from these tests indicated that gas-side resistance is rate controlling at an inlet pH of 9.5 and Na^+ concentration greater than 0.5 wt %, or at an inlet pH above 8.5 and Na^+ concentration of 1.0 wt %. These results are, generally, in agreement with predictions made with the use of the Bechtel modified Radian equilibrium computer program (see Appendix G).

The following theoretical expression represents SO_2 absorption for the condition of gas-side resistance being rate-controlling (Reference 17):

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-k_G a \cdot Z/G\right] \qquad (13\text{-}1)$$

where:

k_G = gas-side mass transfer coefficient, lb-mole/hr ft^2
a = gas-liquid interfacial area per scrubber volume, 1/ft
Z = axial distance, ft
G = gas rate per cross-sectional area, lb-mole/hr ft^2

For each of the scrubber systems an equation of this form was fitted to the soda-ash data meeting the criterion that gas-side resistance was controlling. It will be noted that for each equation correlating the data, the expression in the brackets is equivalent to $k_G a \cdot Z/G$, the number of mass transfer units.

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[*] Note in Appendix D, Table D-10, that Runs 202-1A and 202-1D gave the same absorption efficiency at different Na^+ concentrations, and that Runs 250-1A through 250-1B showed no effect of SO_2 inlet gas concentration on percent SO_2 removal.

13.1.1 Venturi Scrubber

The following equations for predicting SO_2 removal in the Chemico venturi were fitted to the data from the gas-side resistance tests:*

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-0.0049\, v_t^{-1.27} (L/G)^{0.44} (\ell/D)^{0.4}\right] \quad (13\text{-}2)$$

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-0.76\, \Delta p^{0.56}\right] \quad (13\text{-}3)$$

where:

Δp = pressure drop across venturi, in. H_2O
v_t = gas velocity at throat, ft/sec
L/G = liquid-to-gas ratio through scrubber, gal/mcf
ℓ = throat length, ft
D = venturi plug diameter, ft

Either of these equations can be used for predicting SO_2 removal in the venturi. There was insufficient data to develop a correlation for the spray tower in the venturi/spray tower system.

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*See Section 12.1 for equations relating throat length and throat area to percent opening of venturi plug.

Comparisons between measured and predicted SO_2 removals from Equations 13-2 and 13-3 are shown in Figures 13-1 and 13-2. Equations 13-2 and 13-3 account for 99 percent and 96 percent of the variation in the data, respectively.* The standard errors of estimate are 1.2 percent SO_2 removal for Equation 13-2 and 1.9 percent for Equation 13-3.

13.1.2 TCA Scrubber as a Spray Tower

Gas-side resistance tests in the TCA scrubber in its normal configuration resulted in SO_2 removal in excess of 99 percent (Table D-13, Runs 201-2A and 201-2B) and no correlation was possible. However, in tests with the TCA scrubber operated as a spray tower with no screens or spheres (Table D-13, Runs 225-2C through 230-2C), SO_2 removal ranged from 90 to 96 percent. The expontential pre-constant in the following equation for predicting SO_2 removal was fitted to this data:

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-0.34\, v^{-0.2} (L/G)^{.4}\right] \qquad (13\text{-}4)$$

where:

v = gas velocity through scrubber, ft/sec
L/G = liquid-to-gas ratio through scrubber, gal/mcf

Coefficients for liquid and gas rates in the above correlation were obtained from the equation developed in Reference 18 for spray towers, which was based upon the work of Fair (Reference 19). The SO_2 removal fit explains 65 percent of the variation in the data with a standard error of 1.3 percent removal.

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*See Appendix L for definitions of statistical terms.

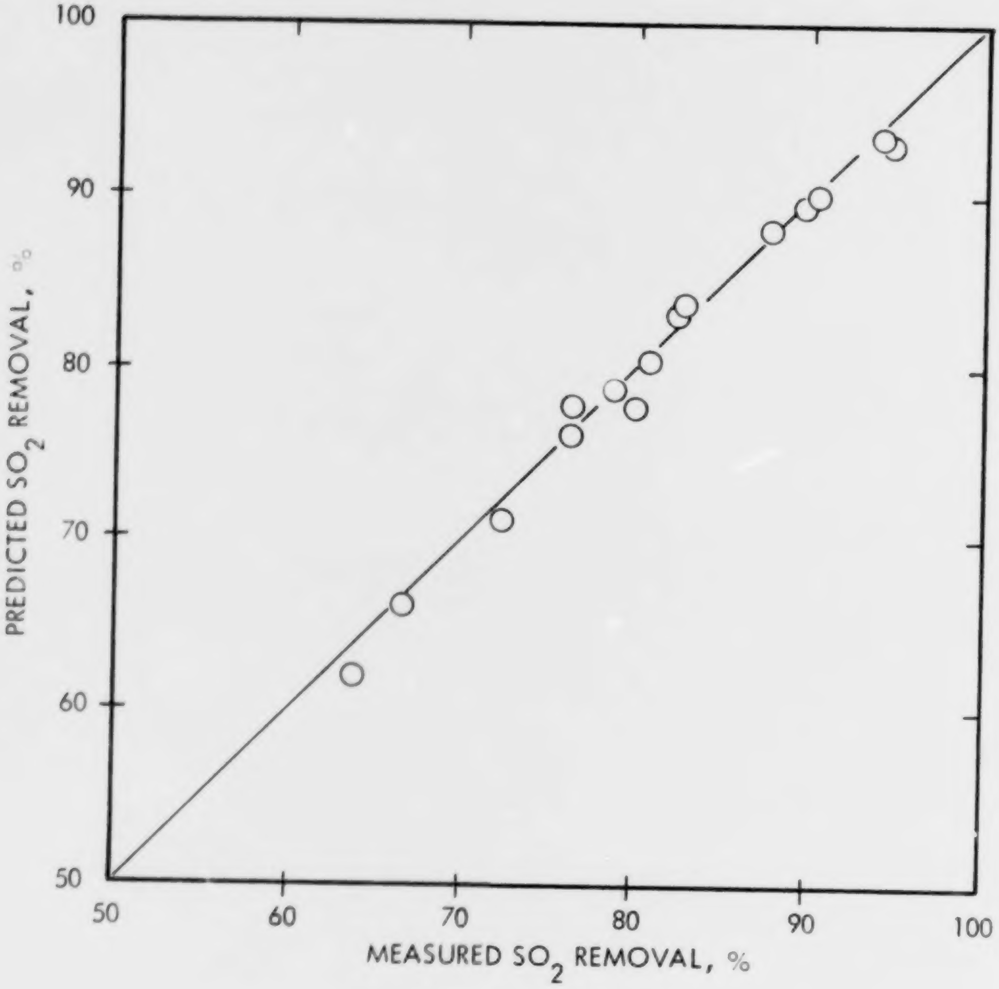

Figure 13-1. Comparison of Experimental Data and Predicted Values of SO_2 Removal in Chemico Venturi from Equation 13-2 (Gas-Side Resistance Tests)

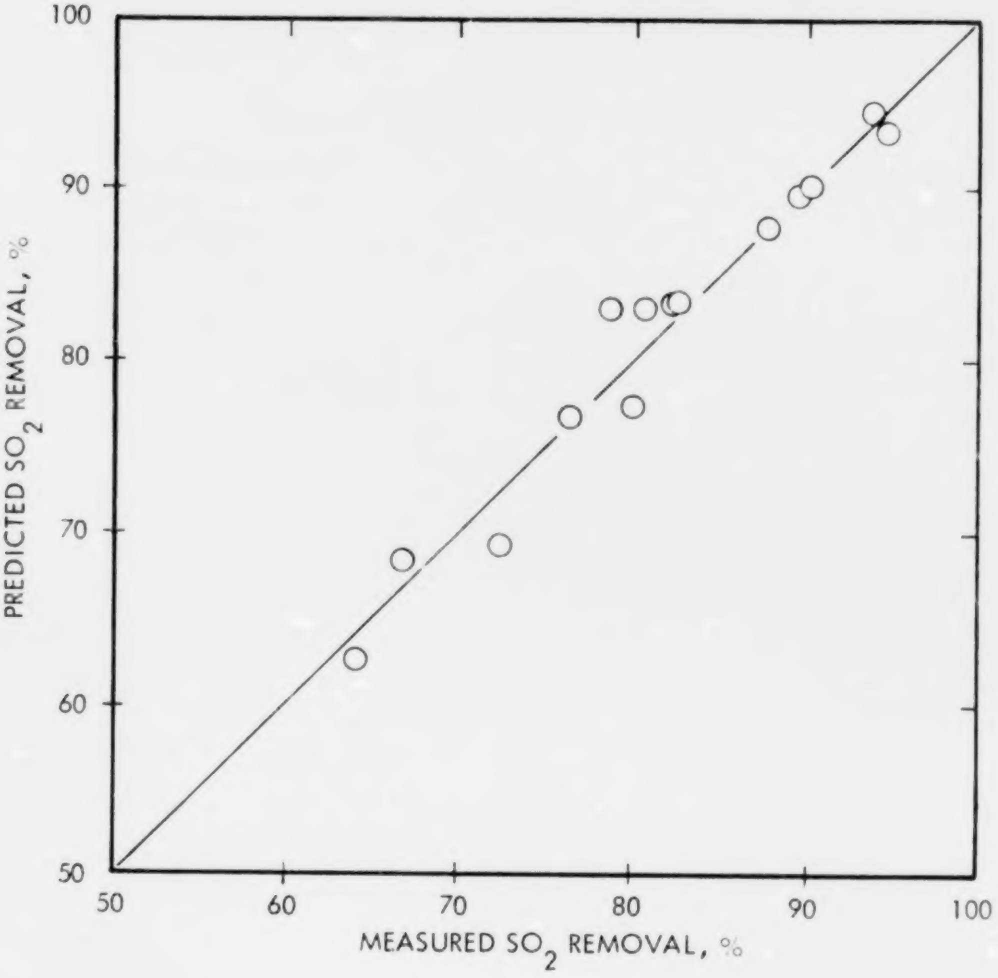

Figure 13-2. Comparison of Experimental Data and Predicted Values of SO_2 Removal in Chemico Venturi from Equation 13-3 (Gas-Side Resistance Tests)

13.1.3 Marble-Bed Scrubber

The two pre-constants in the following equation were fitted to the data from the gas-side resistance tests for the Marble-Bed scrubber (Tables D-15 and D-16):

$$\text{Fraction SO}_2\text{ Removal} = 1 - \exp\left[-3.1\,v^{-0.15}(L/G)^{0.2} Z_M + 0.40\,v^{-0.20}(L/G)^{0.4}\right] \quad (13\text{-}5)$$

where:

v = gas velocity through scrubber, ft/sec

L/G = liquid-to-gas ratio through scrubber, gal/mcf (includes both top and bottom sprays)

Z_M = height of marble layer, ft

The coefficients for liquor and gas rates in the first term of the exponential in Equation 13-5 were obtained from the equation presented in Reference 6 for the $k_G a$ in the glass sphere region of the Marble-Bed system.

The effects of the turbulent layer and of the upper and lower spray zones on $k_G a$ cannot be easily separated, as these effects show a similar variation with liquor and gas rates. Hence, the spray and turbulent layer effects have been combined into a single term (the second term in the exponential of Equation 13-5), with the same coefficients of gas and liquor rates as those developed in Reference 18 for a spray tower.

The SO_2 removal fit in Equation 13-5 explains 79 percent of the variation in the data with a standard error of 1.1 percent removal.

13.2 GAS/LIQUID-SIDE RESISTANCE DATA

"Gas/liquid-side resistance" tests were made under conditions of significant gas-side and liquid-side mass transfer resistance and of negligible equilibrium vapor pressure, y^*, of SO_2 over the bulk liquid. Such conditions existed at Na^+ concentration less than 0.6 wt % and inlet pH greater than 8.5. A correlation was made with the data from the gas/liquid side tests for the Chemico venturi.

In the case of significant gas and liquid-side mass transfer resistance and negligible equilibrium vapor pressure of SO_2 over the bulk liquid, the following expression represents SO_2 absorption (Reference 17):

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[\frac{-k_G a \cdot Z/G}{1 + m\, k_G a / k_L a}\right] \qquad (13\text{-}6)$$

where m is Henry's law constant and k_L is the liquid-side mass transfer coefficient.

For the venturi scrubber, the term $k_G a \cdot Z/G$ can be obtained from Equation 13-2 or 13-3. Using Equation 13-3:

$$k_G a \cdot Z/G = 0.1\,\Delta p^{0.56} \qquad (13\text{-}7)$$

The following equation for predicting SO_2 removal in the Chemico venturi was obtained by combining Equation 13-7 with Equation 13-6 and by fitting the term $m k_G a / k_L a$ to the gas/liquid-side resistance data:

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[\frac{-0.76\,\Delta p^{0.50}}{1 + 5300\,(y_{SO_2}/x_{Na})/(L/G \cdot 10^{pH})^{0.43}}\right] \qquad (13\text{-}8)$$

where:

Δp = pressure drop across venturi, in. H_2O

L/G = liquid-to-gas ratio through venturi, gal/mcf

y_{SO_2} = mole fraction SO_2 in inlet gas

x_{Na} = mole fraction Na in inlet liquor

pH = liquor pH at scrubber inlet

The proportionality between $m k_G a / k_L a$ and y_{SO_2}/x_{Na} shown in Equation 13-8 can be predicted theoretically. Also, $m k_G a / k_L a$ is expected to be a function of liquid-to-gas ratio and pH. The statistical significance of y_{SO_2}/x_{Na} and of the interaction group $(L/G) \cdot 10^{pH}$ was verified by a linear regression model.

Measured and predicted values of SO_2 removal from Equation 13-8 are compared in Figure 13-3. Equation 13-8 explains 85 percent of the variation in the data with a standard error of estimate of 4.1 percent SO_2 removal.

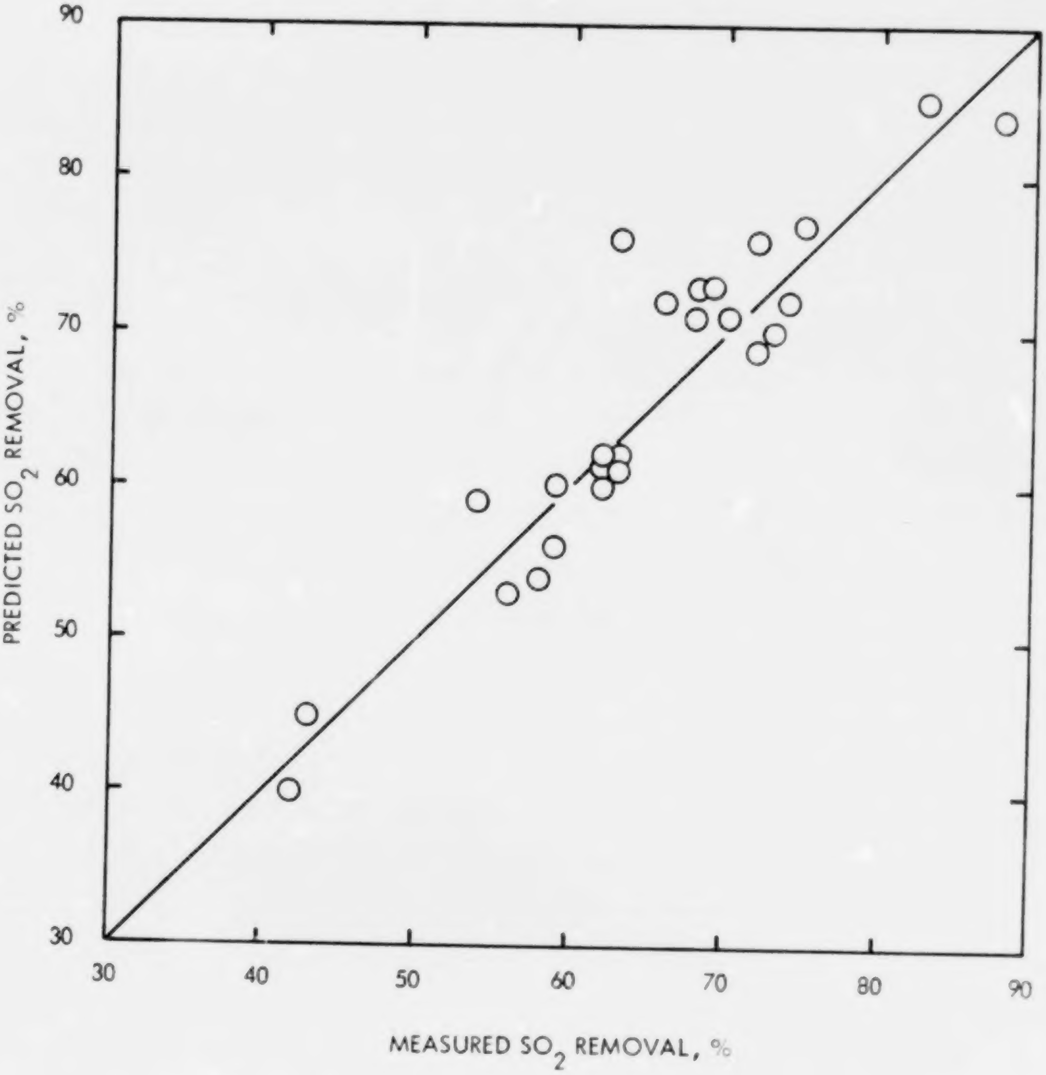

Figure 13-3. Comparison of Experimental Data and Predicted Values of SO_2 Removal in Chemico Venturi from Equation 13-8 (Gas/Liquid-Side Resistance Tests)

Section 14

ANALYSIS OF LIMESTONE FACTORIAL DATA

In this section, a theoretical approach is employed to relate SO_2 removal to the measured parameters for the spray tower, TCA, and Marble-Bed absorbers. A closed-form equation is developed for each absorber, which is compatible with boundary constraints, and which should permit reasonable extrapolations. Variables which were found to be significant by a statistical analysis of the data were introduced into the closed-form equations.

14.1 THEORETICAL MODEL

Analysis of the limestone factorial data, using the Bechtel modified Radian Equilibrium Computer Program (see Appendix G), has shown that the equilibrium mole fraction of SO_2 over the bulk scrubber liquid, y^*, is negligible with respect to the SO_2 mole fraction within the gas for the spray tower, TCA, and Marble-Bed scrubbers.* For this condition, Equation 13-6 represents SO_2 removal:

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[\frac{-k_G a Z/G}{1 + m k_G a/k_L a}\right] \qquad (13\text{-}6)$$

---

*Due to low liquor residence times, the amount of limestone dissolved within the venturi scrubber is relatively small. Hence, y^* can be significant.

where:

k_G = gas-side mass transfer coefficient

a = gas-liquid interfacial area per scrubber volume

Z = axial distance in the scrubber

G = gas rate per cross-sectional area

m = Henry's law constant

k_L = liquid-side mass transfer coefficient

Also, scrubber computer models using previously fitted gas-side mass transfer coefficients (see Section 13) have shown that liquid-side resistance controls (i.e., $k_L/m \ll k_G$) for the spray tower, TCA, and Marble-Bed scrubbers for a majority of the limestone data. For this condition, Equation 13-6 can be written as:

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-k_L a Z/mG\right] \qquad (14\text{-}1)$$

The liquid-side coefficient can be written as:

$$k_L = \phi k_L^{o} \qquad (14\text{-}2)$$

where:

k_L^{o} = liquid film mass transfer coefficient for physical absorption

ϕ = average enhancement factor for mass transfer in the liquid film due to chemical reaction within the scrubber

It is assumed that the parameters k_L^o, a, and z are functions of gas rate, liquor rate, and scrubber internals (e.g., number of stages in the TCA), and that ϕ is a function of the reactions within the scrubber liquor.

As an example of the approximation to the actual conditions encountered during alkali wet-scrubbing of SO_2, consider a very rapid pseudosecond order irreversible reaction between the absorbed gas A (H_2SO_3) and "reagent" B (bicarbonate and sulfite species). If the diffusivities of A and B in the liquid are equal, the following expression can be used to predict the enhancement factor (see Equation 26 in Reference 6):

$$\phi = 1 + \frac{X_B}{\nu X_A} \qquad (14\text{-}3)$$

where:

X_B = average concentration of dissoved reactant B (bicarbonate and sulfite species) in the scrubber liquor

X_A = average concentration of dissolved A (H_2SO_3) at the gas-liquid interface within scrubber

ν = stoichiometric coefficient relating the number of moles of B reacting with one mole of A

For liquid-side controlling mass transfer, X_A can be approximated by:

$$X_A = y/m \qquad (14\text{-}4)$$

where y is the SO_2 concentration in the scrubber gas phase.

An analysis of the limestone factorial analytical data with the use of the Radian computer program has shown that X_B is inversely proportional to the hydronium ion concentration of the scrubber liquor:

$$X_\beta = \beta \frac{1}{[H^+]} = \beta\, 10^{pH} \qquad (14\text{-}5)$$

where β is a constant and pH is the scrubber liquor pH.

The enhancement factor, therefore, may be written as:

$$\phi = 1 + \beta' \frac{10^{pH}}{y} \qquad (14\text{-}6)$$

where β' is a constant equal to $m\beta/\nu$.

Combining Equations 14-1, 14-2, and 14-6 yields:

$$\begin{array}{l}\text{Fraction} \\ \text{SO}_2 \text{ Removal}\end{array} = 1 - \exp\left[-\frac{k_L a Z}{m G}\left(1 + \beta' \frac{10^{pH}}{y}\right)\right] \qquad (14\text{-}7)$$

The form of Equation 14-7 has been fitted by multiple regression to the limestone factorial data for the spray tower, TCA, and Marble-Bed scrubbers. For these fitted equations, the scrubber inlet liquor pH and the scrubber inlet gas SO_2 concentration have been substituted for the average values of pH and SO_2 concentration in Equation 14-7.

It is assumed that the effect of scrubber inlet liquor pH and inlet gas SO_2 concentration on SO_2 removal is represented by the form of Equation 14-7 for the three scrubber systems. However, the variation in scrubber inlet liquor pH (a controlled independent variable) was statistically significant only for the spray tower tests, and the variation in inlet gas SO_2 concentration (a non-controlled independent variable) was statistically significant only for the TCA tests. Therefore, the effects of pH and gas SO_2 concentration on SO_2 removal have been included only in the fitted models for the spray tower and TCA, respectively.

14.2 FITTED EQUATIONS

14.2.1 Spray Tower

The following equation was fitted to 12[*] limestone factorial test runs made with the spray tower (see Figure 6-2 and Table E-4):

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left\{-0.018\, v^{-0.31} (L/G)^{0.74} \times \left[1 + 5.0 \times 10^{-7}\, 10^{pH_i}\right]\right\} \qquad (14\text{-}8)$$

where:

v = superficial gas velocity at scrubber conditions, ft/sec
L/G = liquid-to-gas ratio at scrubber conditions, gal/mcf
pH_i = scrubber inlet liquor pH

Measured and predicted SO_2 removals from Equation 14-8 are shown in Figure 14-1. Equation 14-8 accounts for 94 percent of the variation

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[*] Only data for runs with 300 gpm per header were included. The single data point at 225 gpm per header (Run 523-1A) was omitted.

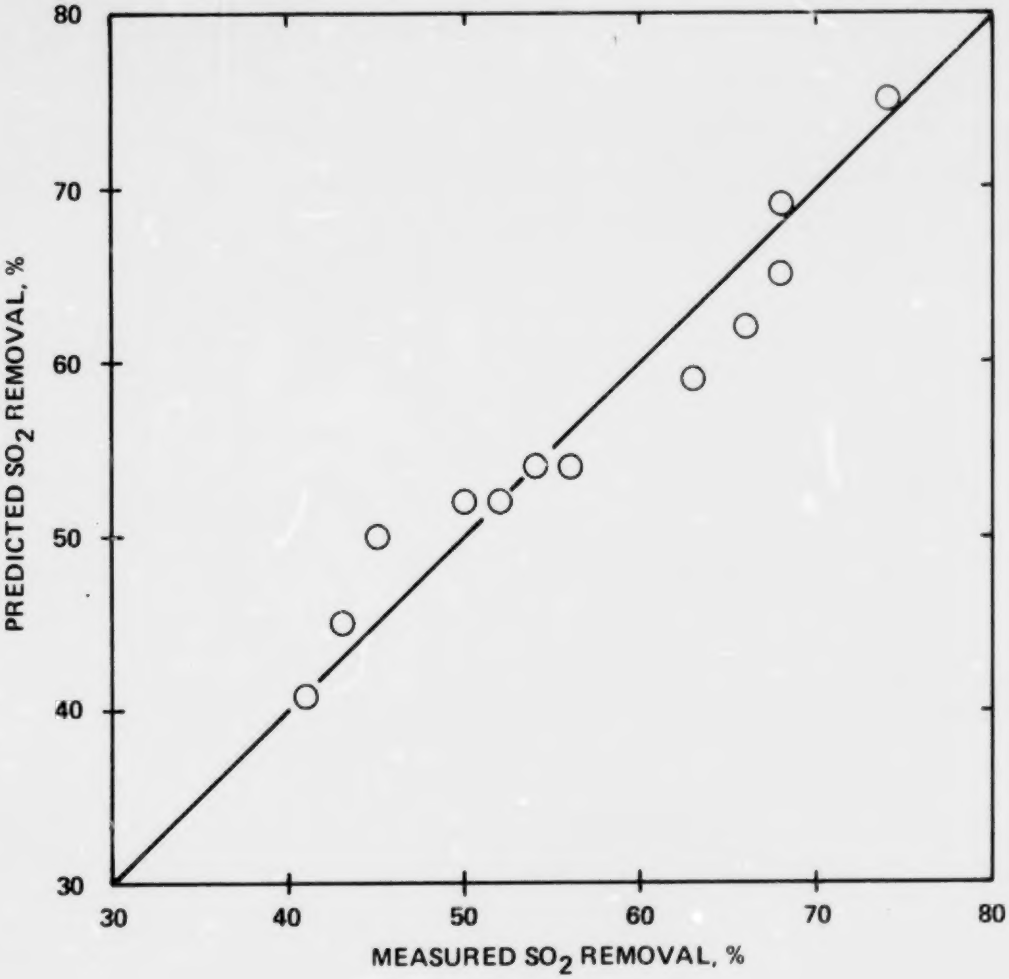

Figure 14-1. Comparison of Experimental Data and Predicted Values of SO_2 Removal in the Spray Tower from Equation 14-8 (Limestone Factorial Tests)

in the data with a standard error of estimate of 3.2 percent SO_2 removal.[*]

14.2.2 TCA Scrubber

The following equation was fitted to 17[**] limestone factorial test runs made with the TCA (see Figures 6-5 and 6-6 and Table E-2):

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \mathrm{Exp}\left\{ -0.0046\, L^{1.28} \left[1 + 0.10 \left(\frac{h_p}{d_p} + N_s \right) \right] \times \left[1 + \frac{3500}{y_i} \right] \right\} \quad (14\text{-}9)$$

where:

L = liquor rate per cross-sectional area, gpm/ft^2

h_p = total height of packing, in.

d_p = diameter of packing = 1.5 in.

N_s = number of grids (screens)

y_i = scrubber inlet gas SO_2 concentration, ppm

Measured and predicted SO_2 removals from Equation 14-9 are shown in Figure 14-2. Equation 14-9 accounts for 98.5 percent of the variation in the data with a standard error of estimate of 1.3 percent SO_2 removal.

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[*] See Appendix L for definitions of statistical terms.

[**] Runs 423-2A and 424-2A were excluded because of high values for solids concentration in the recirculating slurry. Run 427-2A was excluded because it was a limestone depletion run.

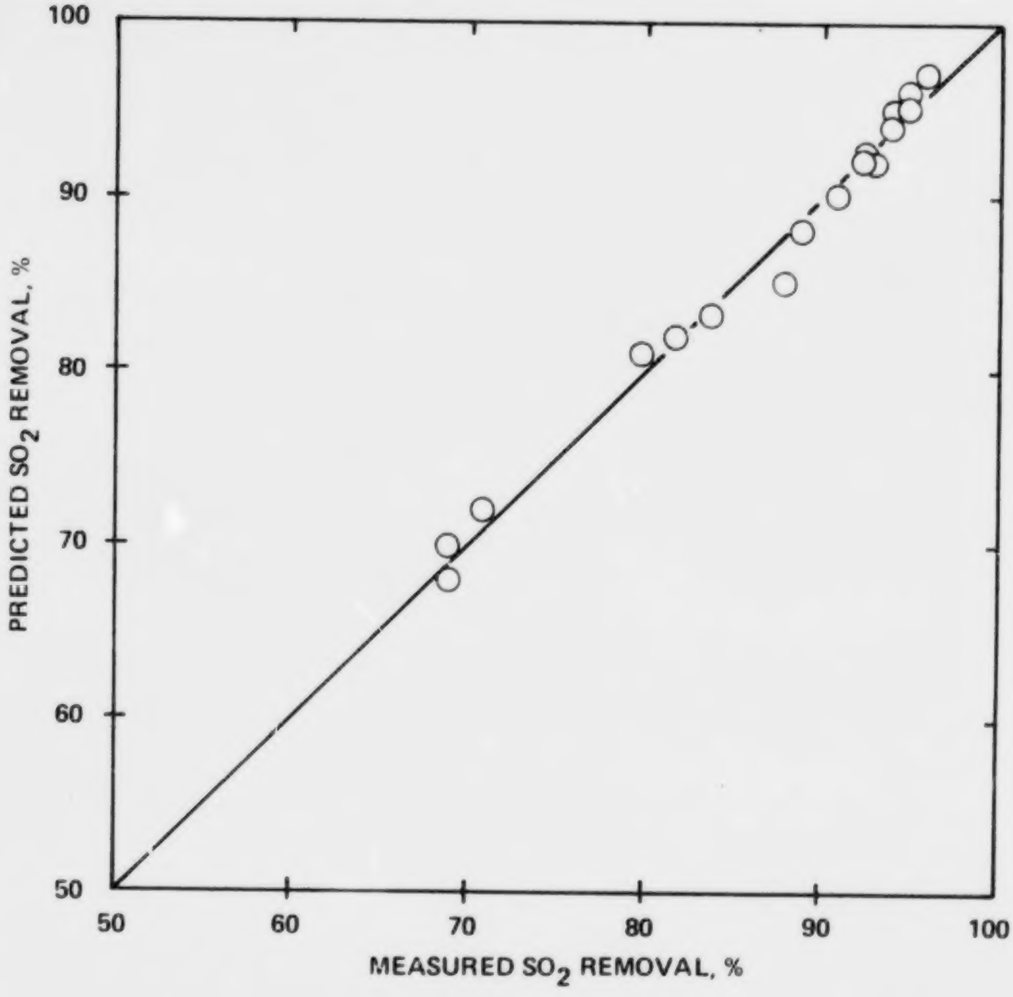

Figure 14-2. Comparison of Experimental Data and Predicted Values of SO_2 Removal in the TCA from Equation 14-9 (Limestone Factorial Tests)

14.2.3 Marble-Bed Scrubber

The following equation was fitted to 27[*] limestone factorial test runs made with the Marble-Bed scrubber (see Figure 6-8 and Table E-3):

$$\text{Fraction } SO_2 \text{ Removal} = 1 - \exp\left[-0.013\, L\, (L/G)^{0.55}\right] \qquad (14\text{-}10)$$

Measured and predicted SO_2 removals from Equation 14-10 are shown in Figure 14-3. Equation 14-10 accounts for 95 percent of the variation in the data with a standard error of estimate of 4.1 percent SO_2 removal.

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[*] Runs 405-3A through 415-3A were excluded because of anomalously low values for SO_2 removal. Run 431-3A was excluded because of unstable operation of the marble bed.

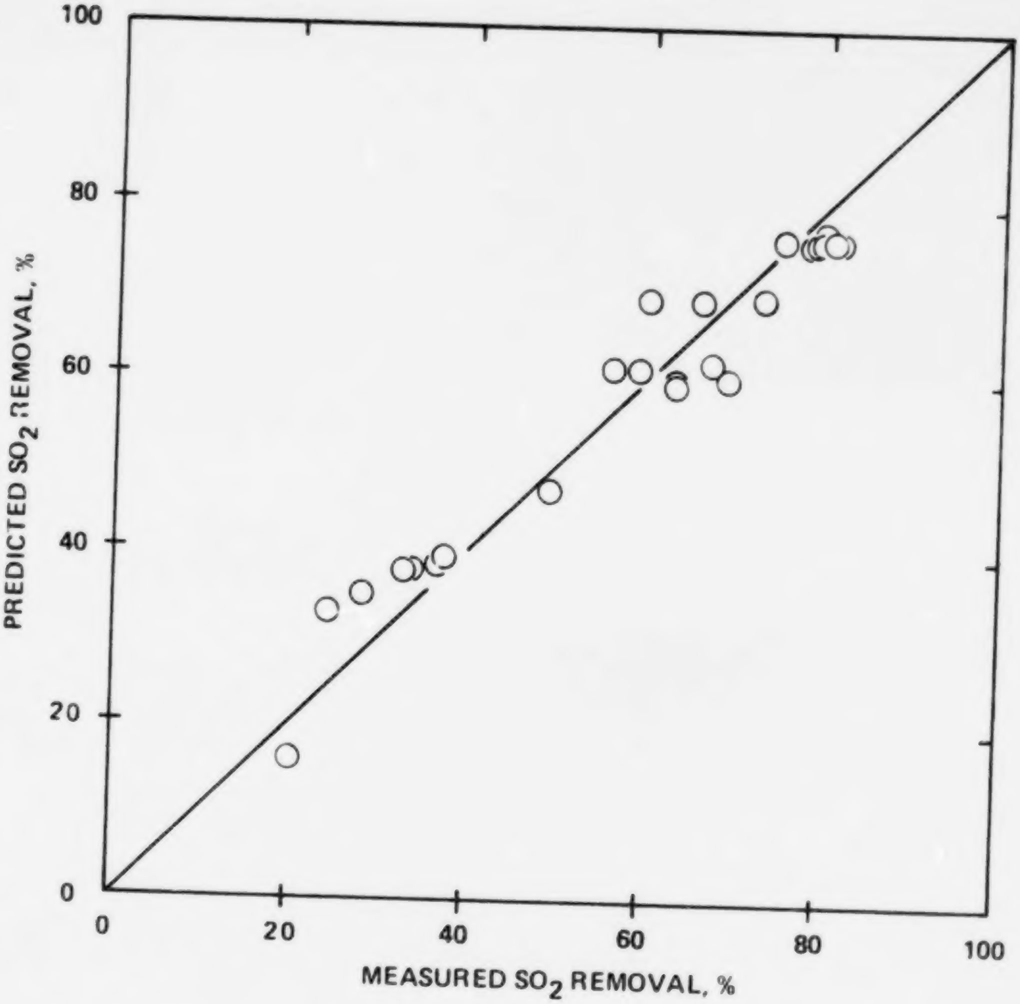

Figure 14-3. Comparison of Experimental Data and Predicted Values of SO_2 Removal in the Marble-Bed Scrubber from Equation 14-10 (Limestone Factorial Tests)

Section 15

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Appendix A

CONVERTING UNITS OF MEASURE

Environmental Protection Agency policy is to express all measurements in Agency documents in metric units. When implementing this practice will result in undue costs or lack of clarity, conversion factors are provided for the non-metric units used in the report. Generally, this report uses British units of measure. For conversion to the metric system, use the following conversions:

To Convert From	To	Multiply By
scfm (60°F)	nm^3/hr (0°C)	1.61
cfm	m^3/hr	1.70
°F	°C	subtract 32 then ÷ 1.8
ft	m	0.305
ft/hr	m/hr	0.305
ft/sec	m/sec	0.305
ft^2	m^2	0.0929
ft^2/tons per day	m^2/metric tons per day	0.102
gal/mcf	ℓ/m^3	0.134
gpm	ℓ/min	3.79
gpm/ft^2	$\ell/min/m^2$	40.8
gr/scf	gm/m^3	2.29
in.	cm	2.54
in. H_2O	mm Hg	1.87
lb	gm	454
lb-moles	gm-moles	454
lb-moles/hr	gm-moles/min	7.56
lb-moles/hr ft^2	gm-moles/min/m^2	81.4
lb-moles/min	gm-moles/sec	7.56

Appendix B

SCRUBBER OPERATING PERIODS

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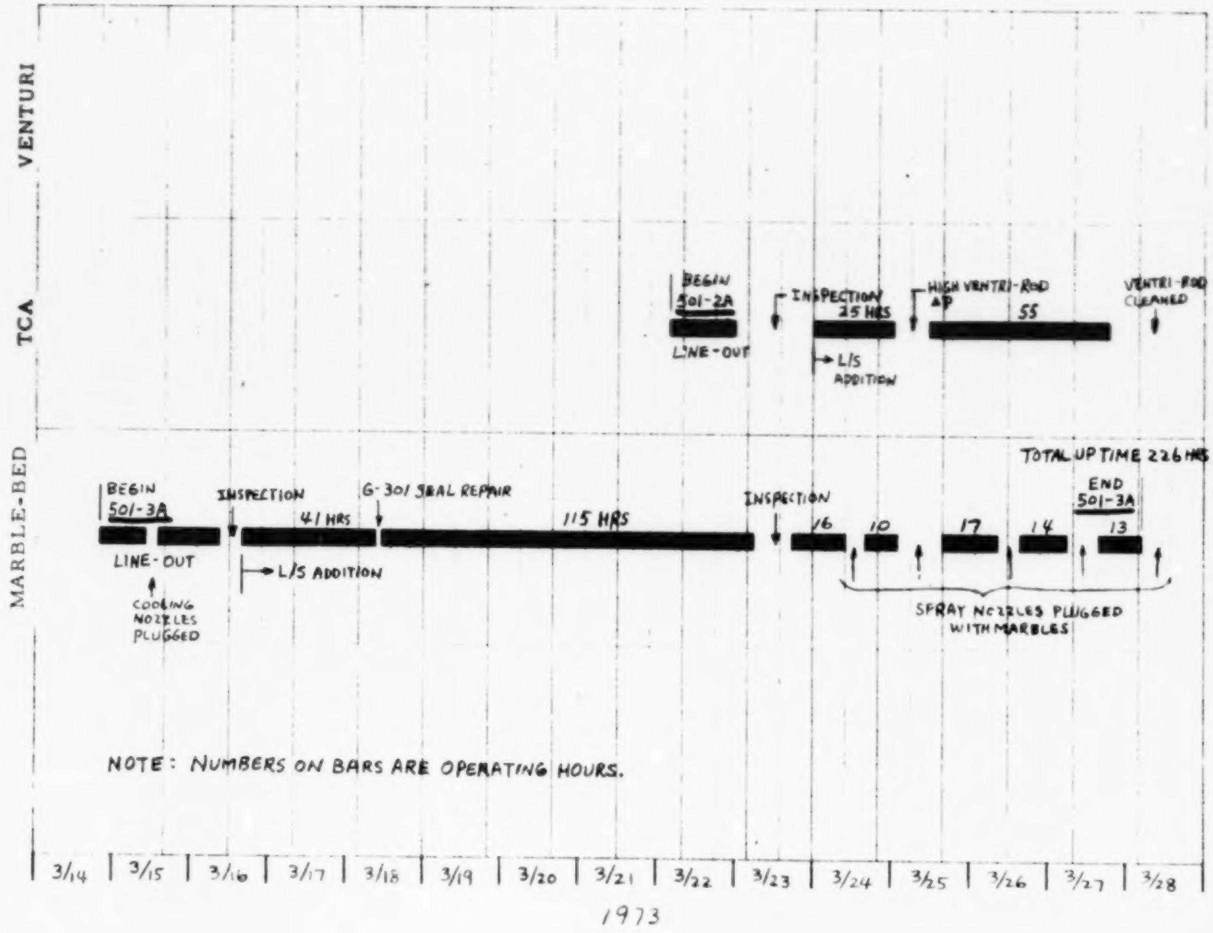

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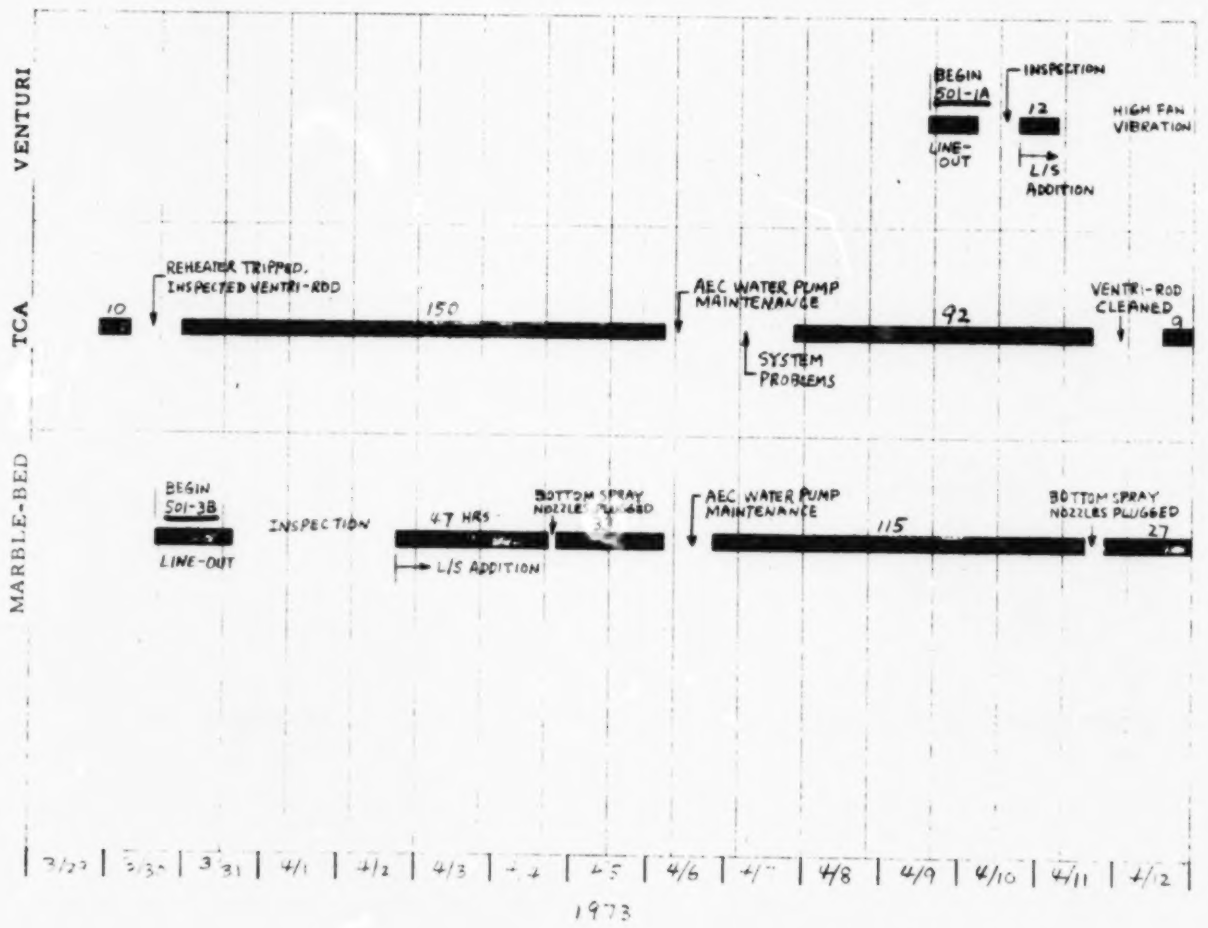

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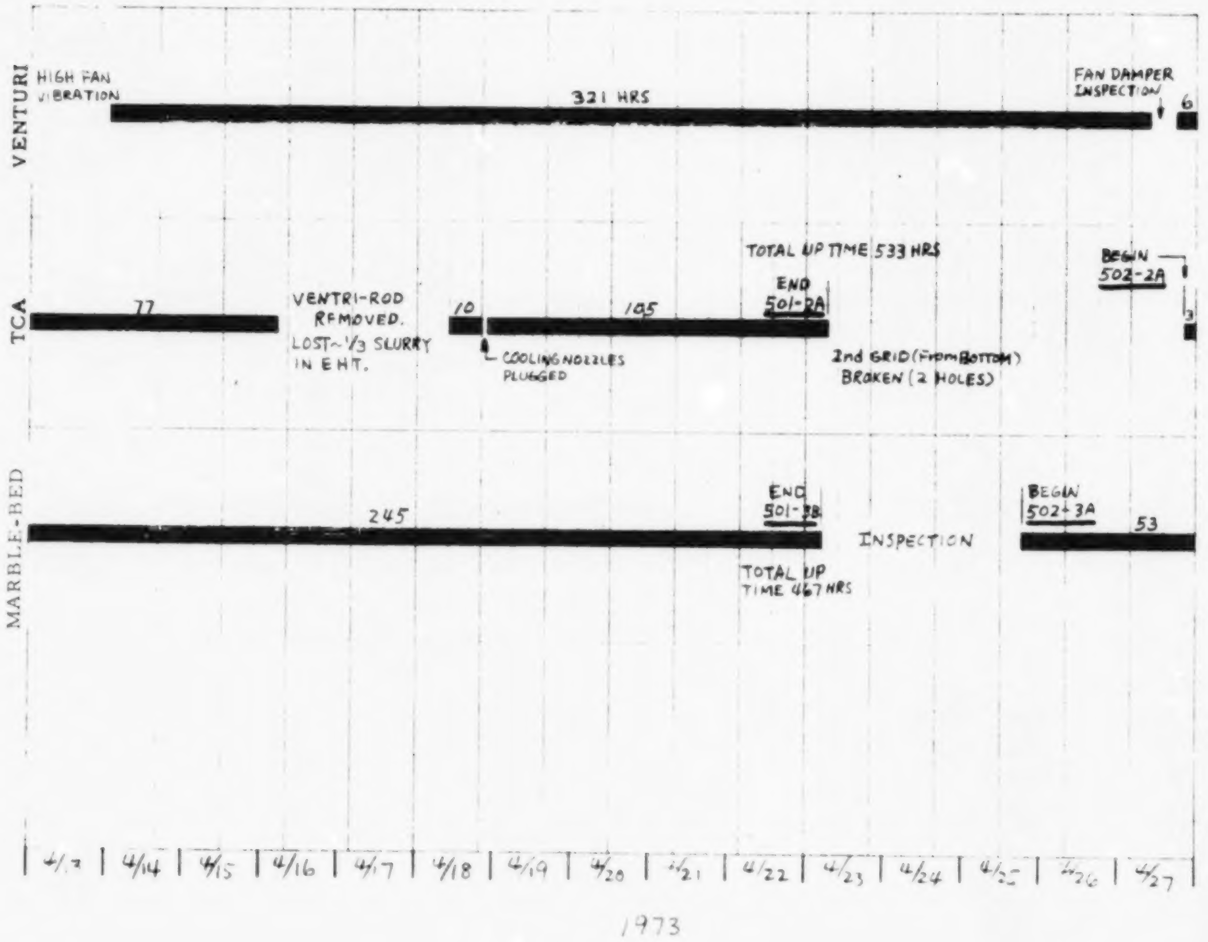

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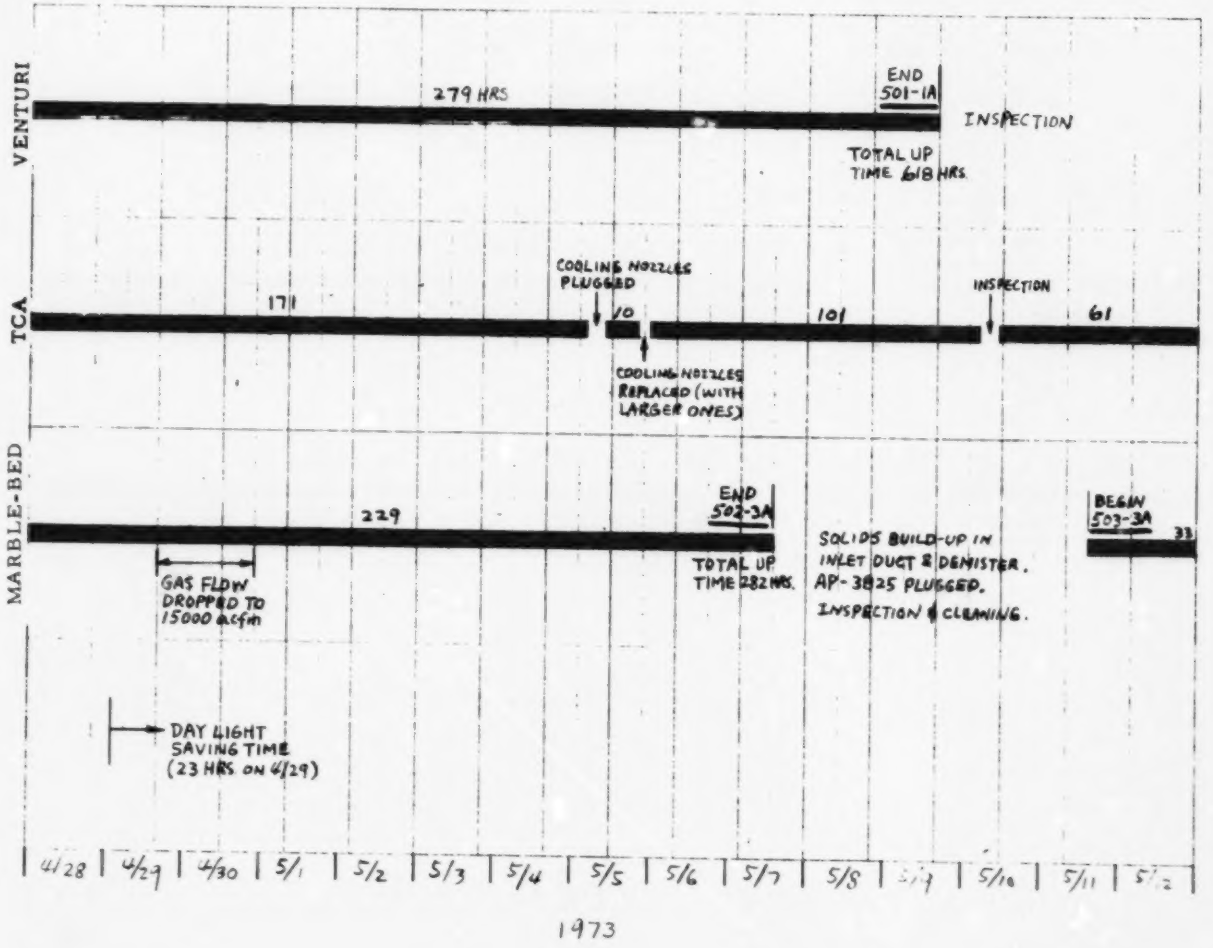

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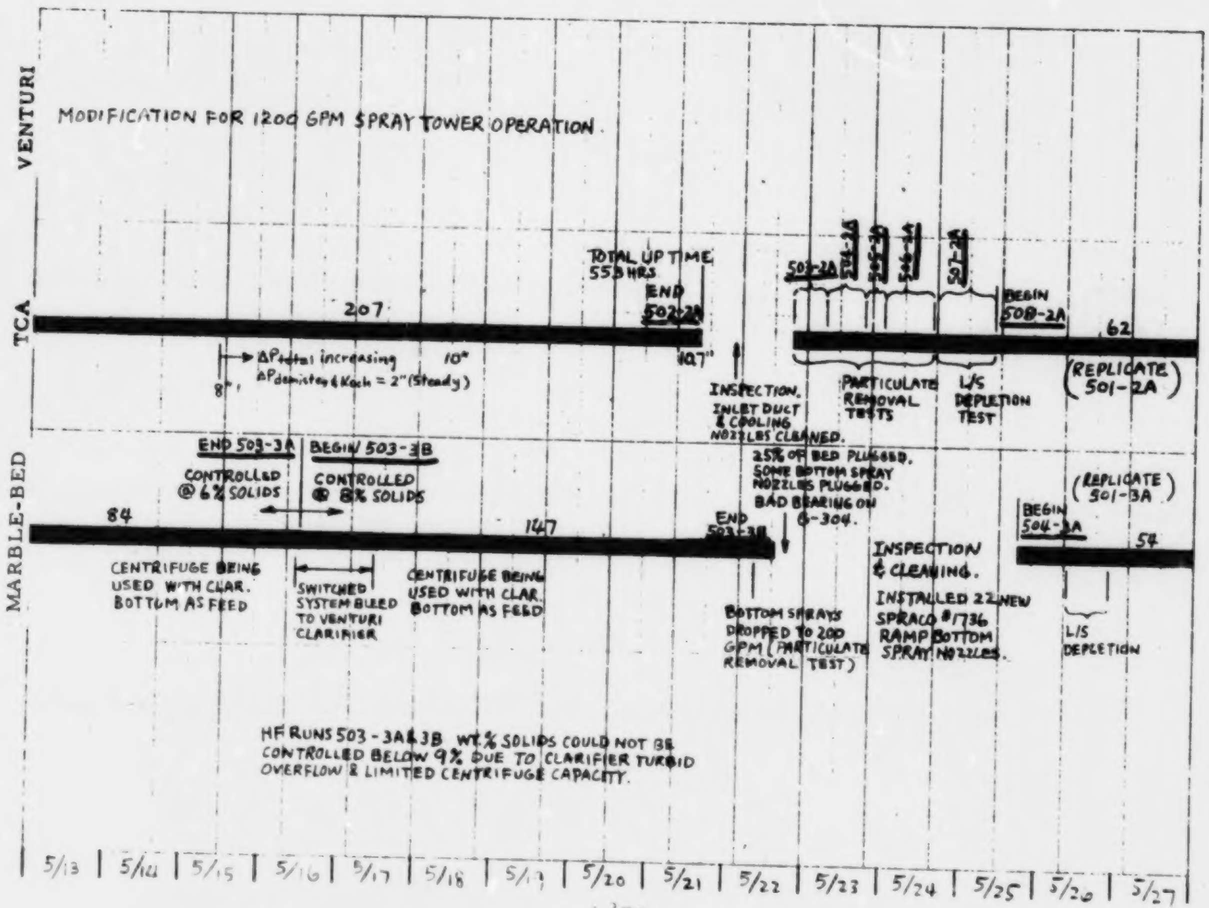

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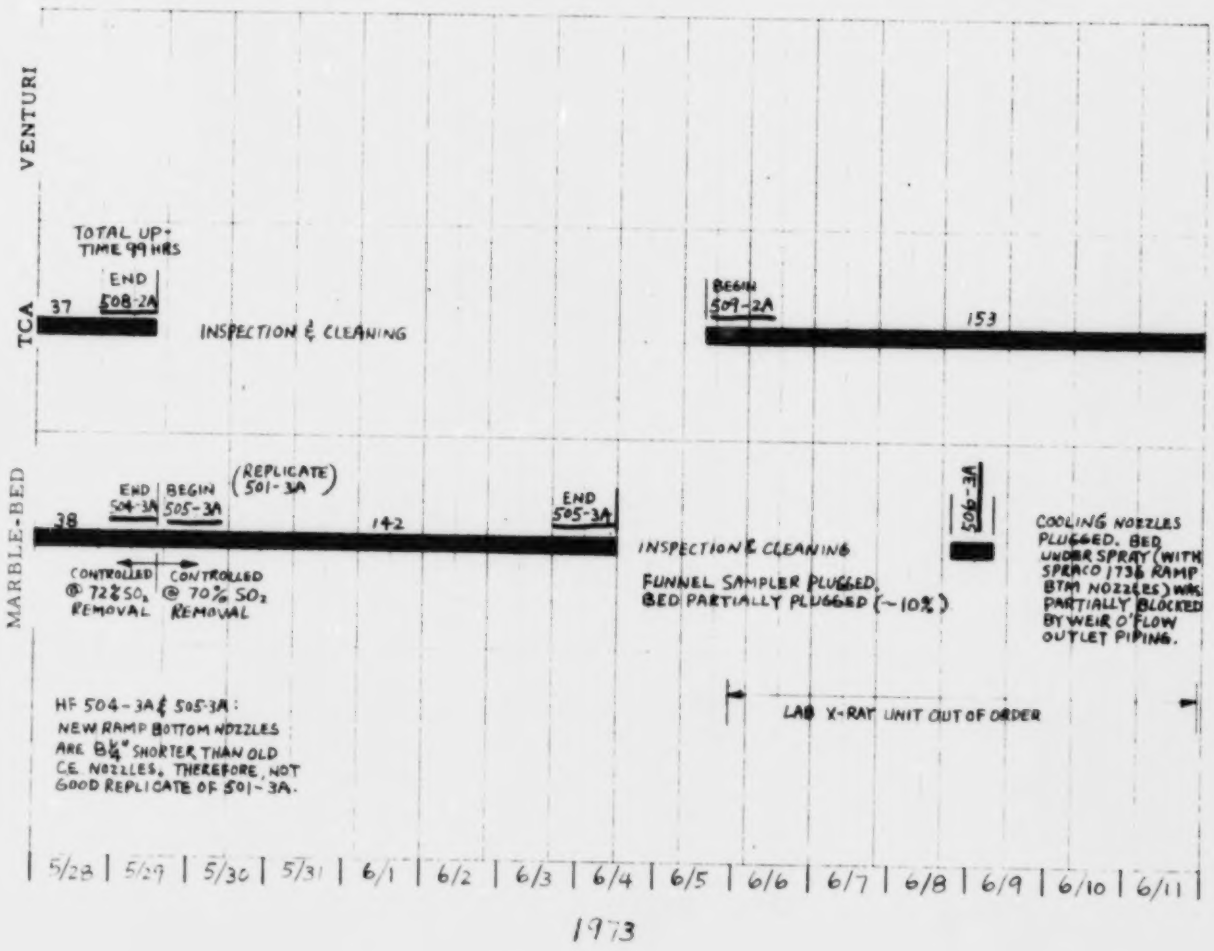

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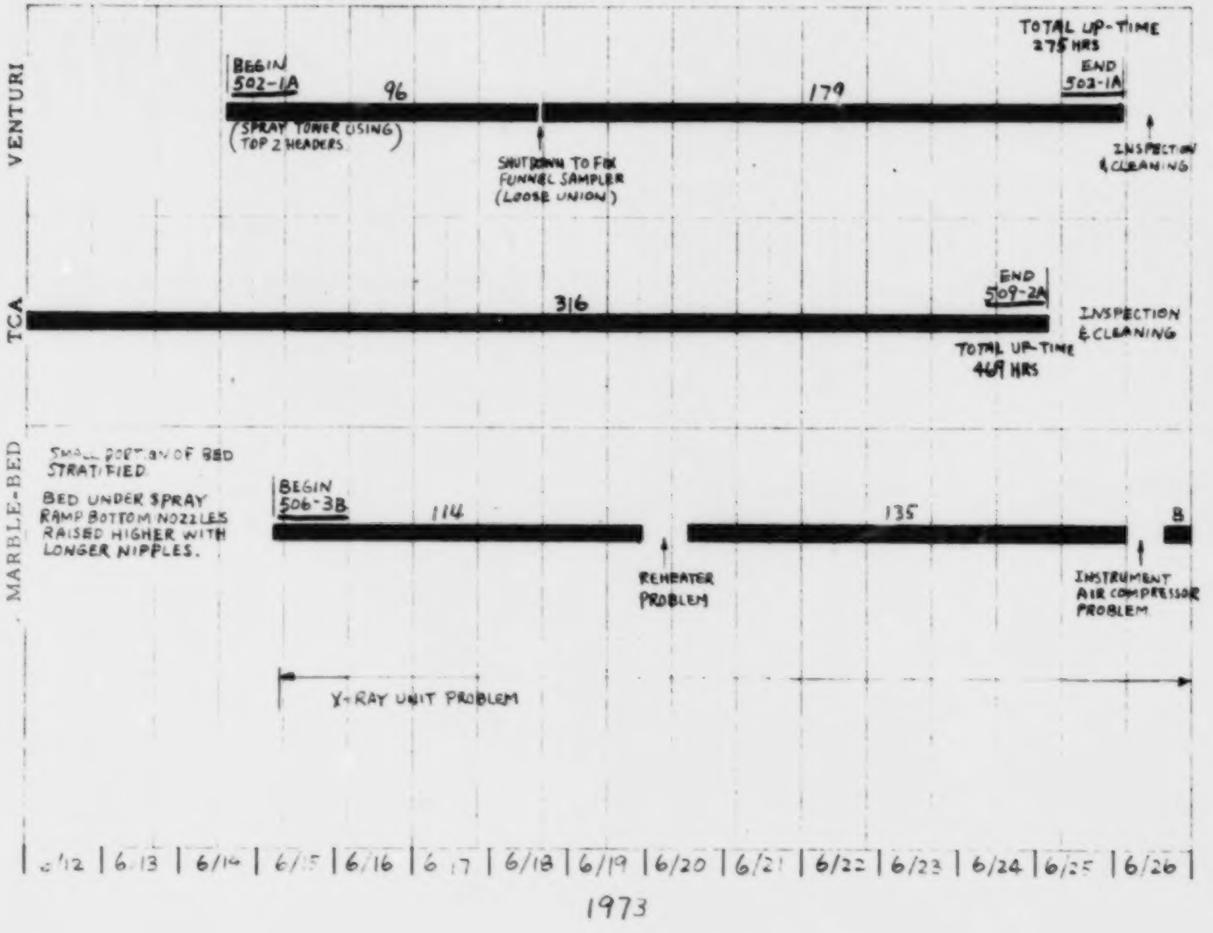

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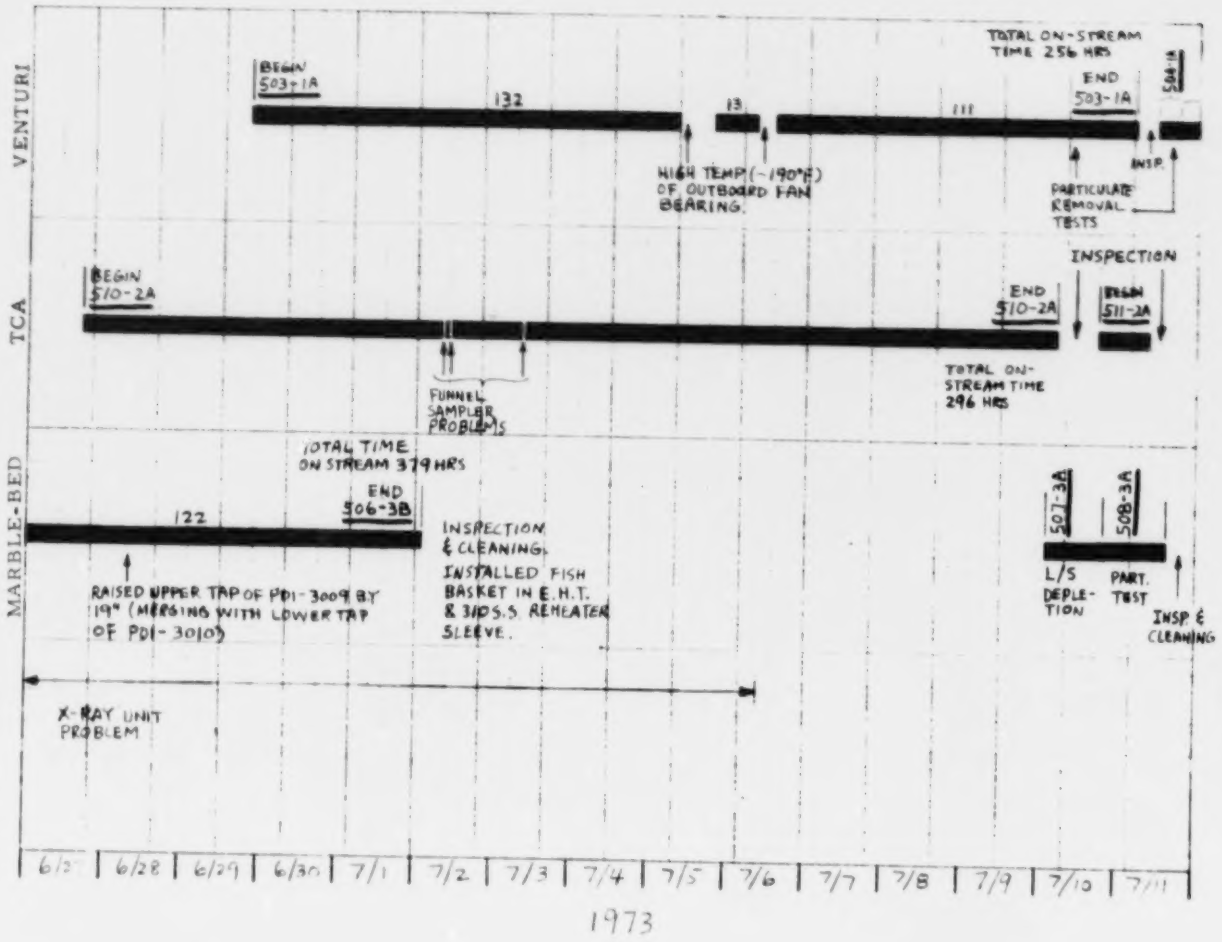

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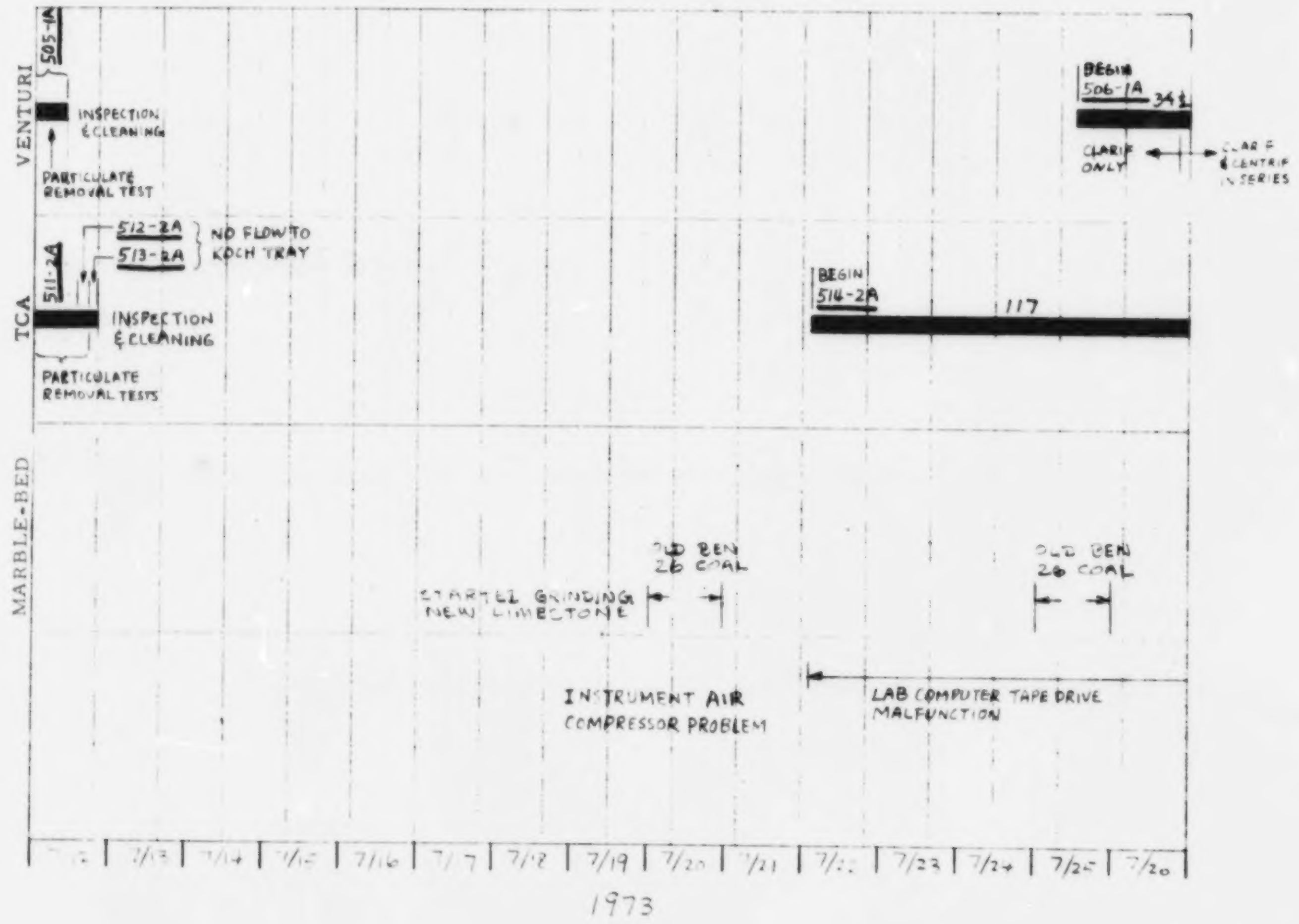

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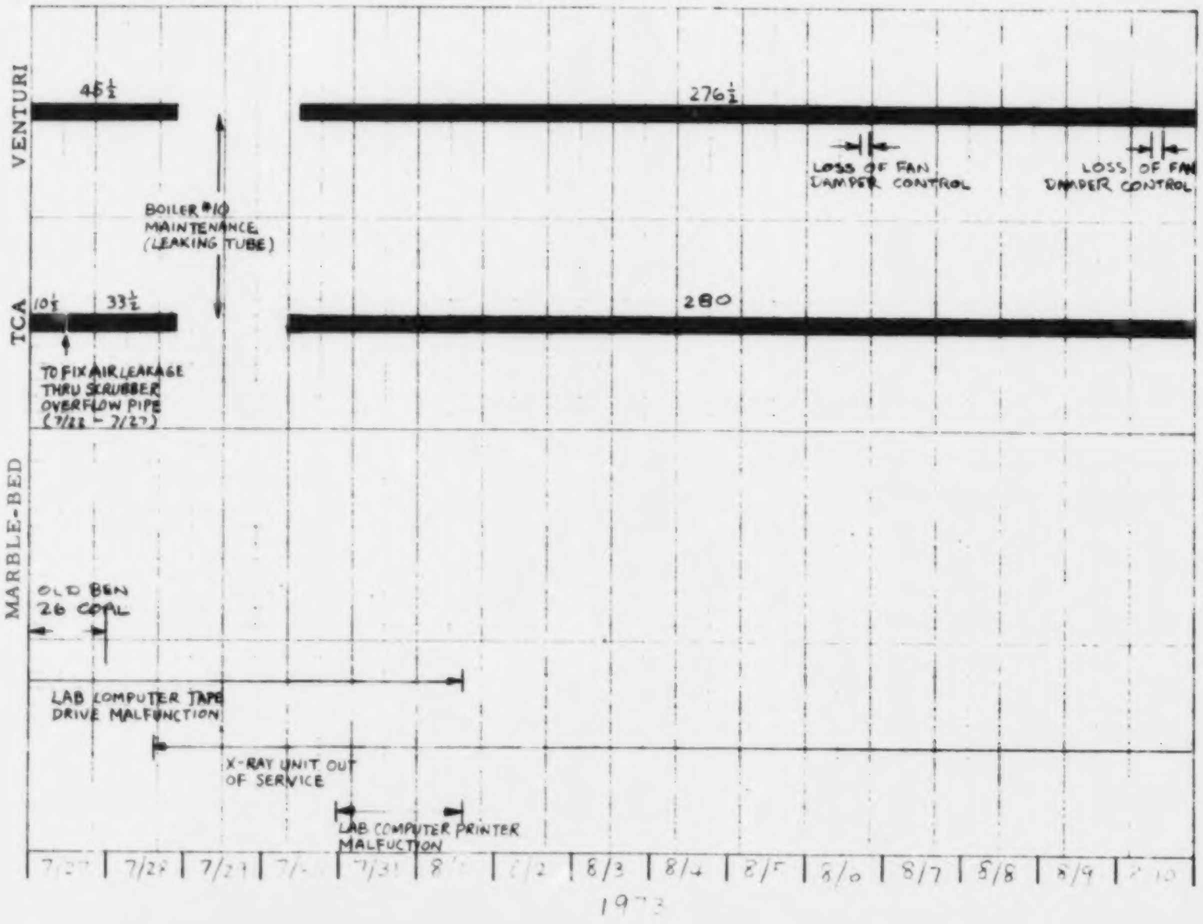

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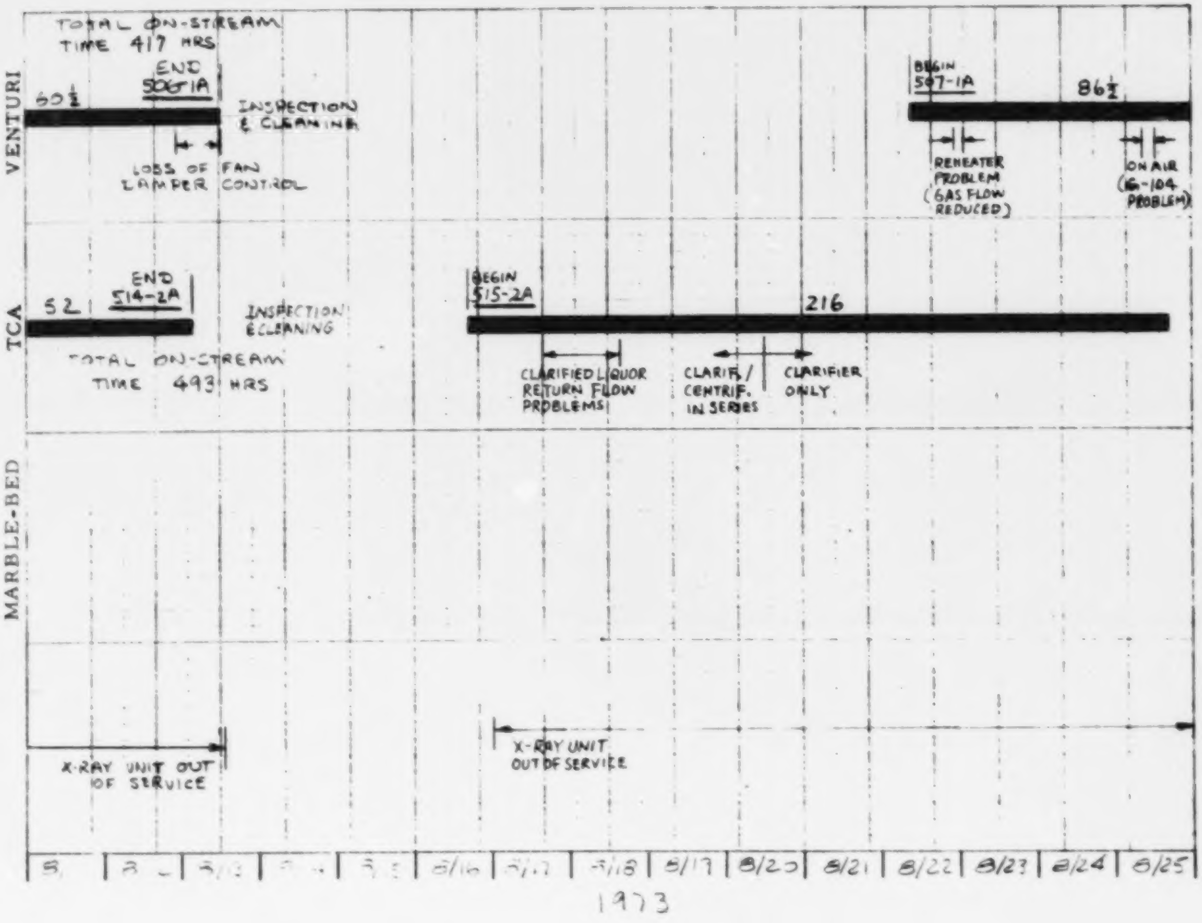

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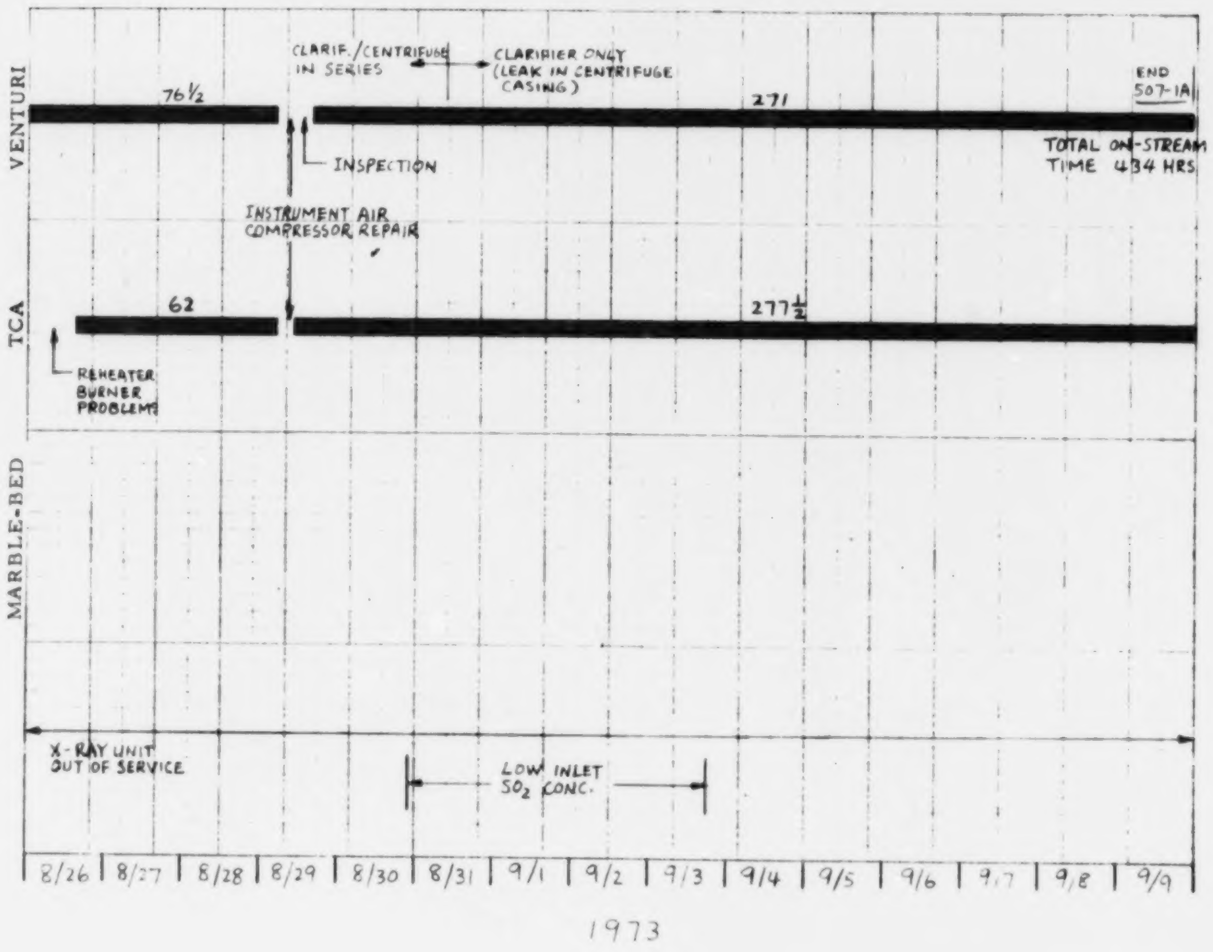

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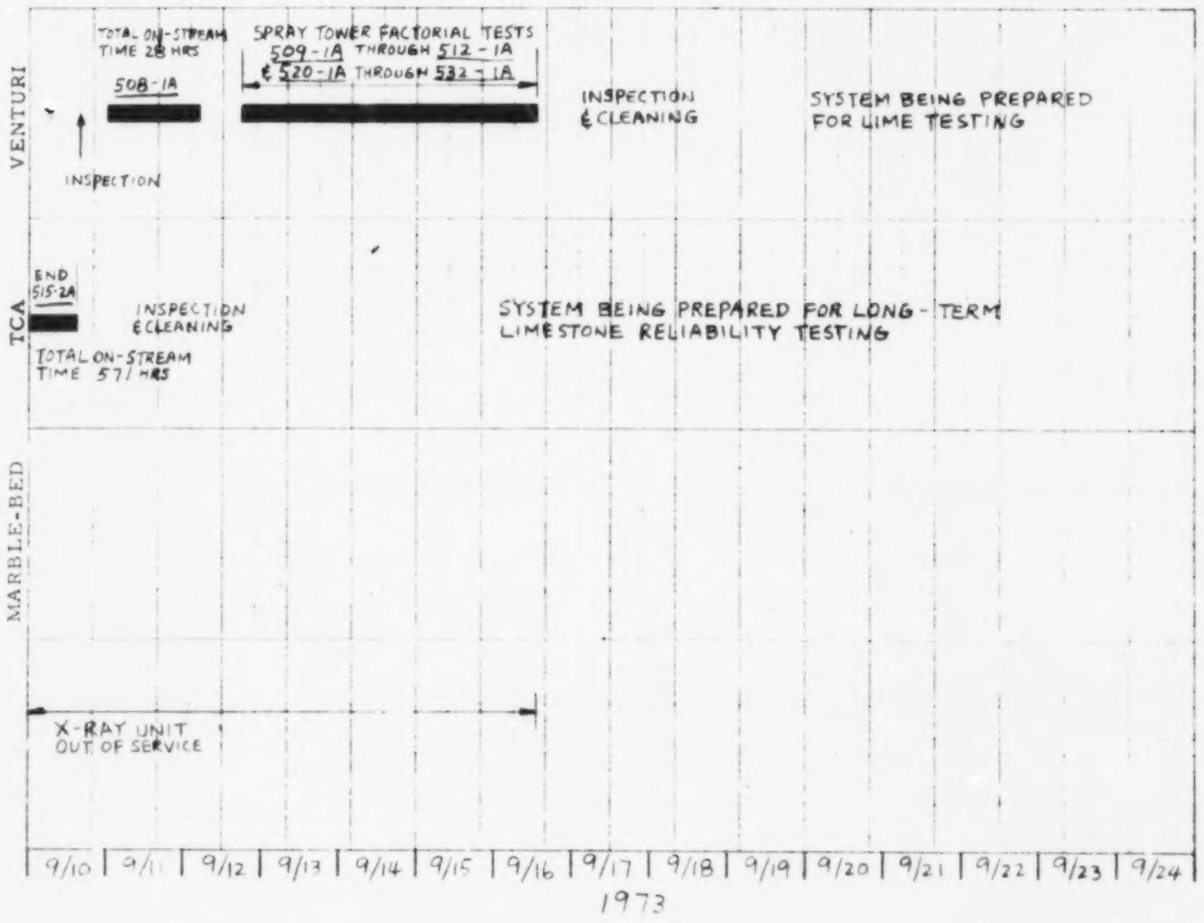

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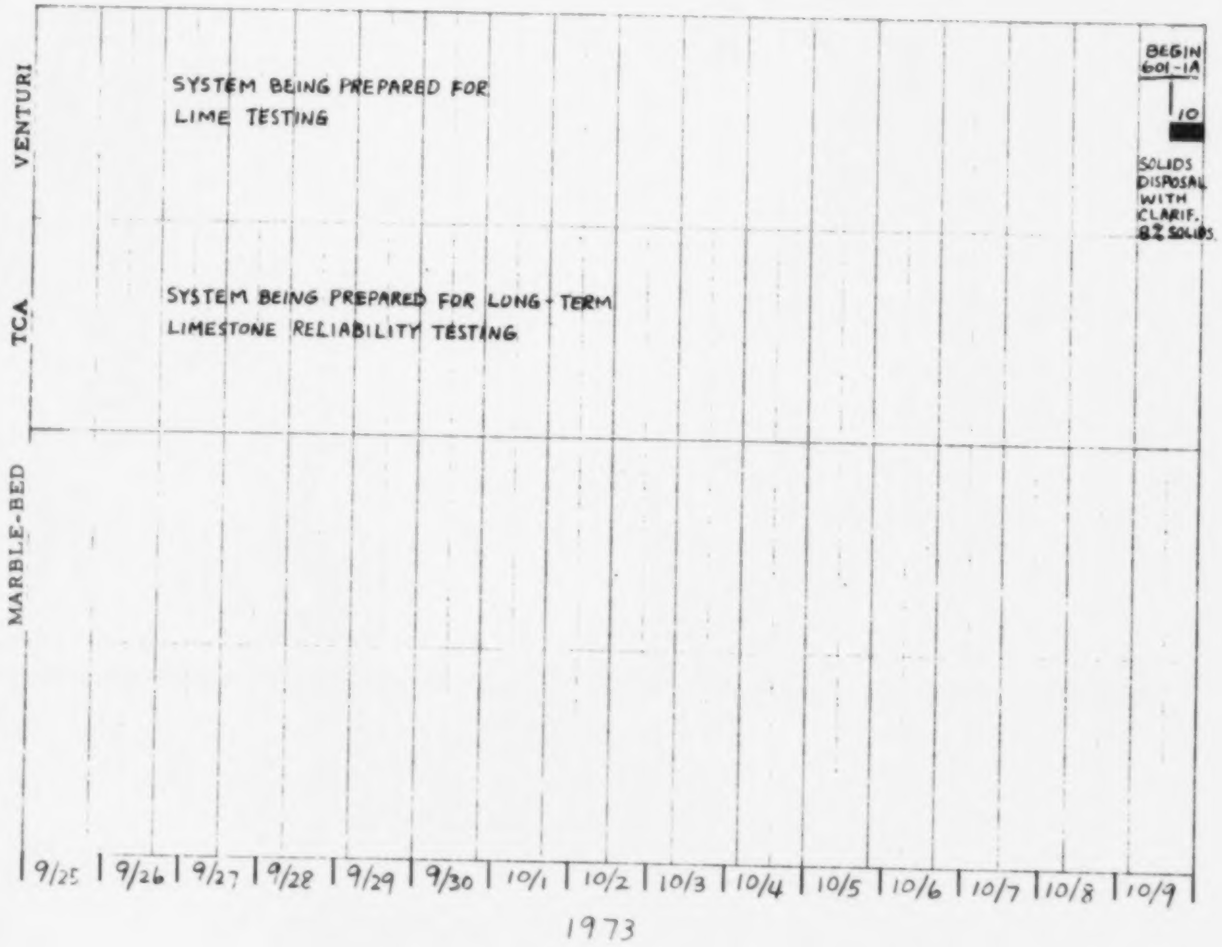

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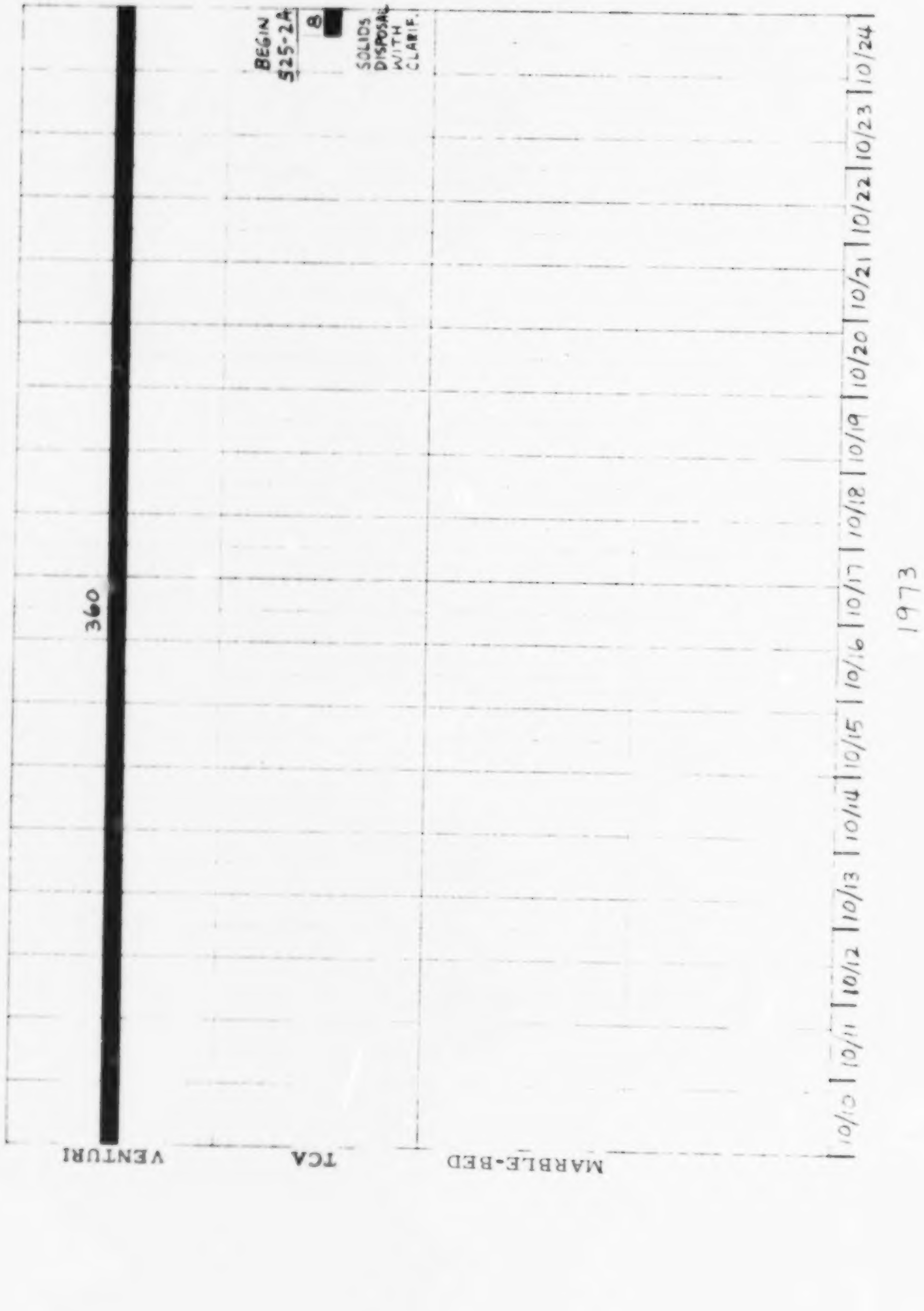

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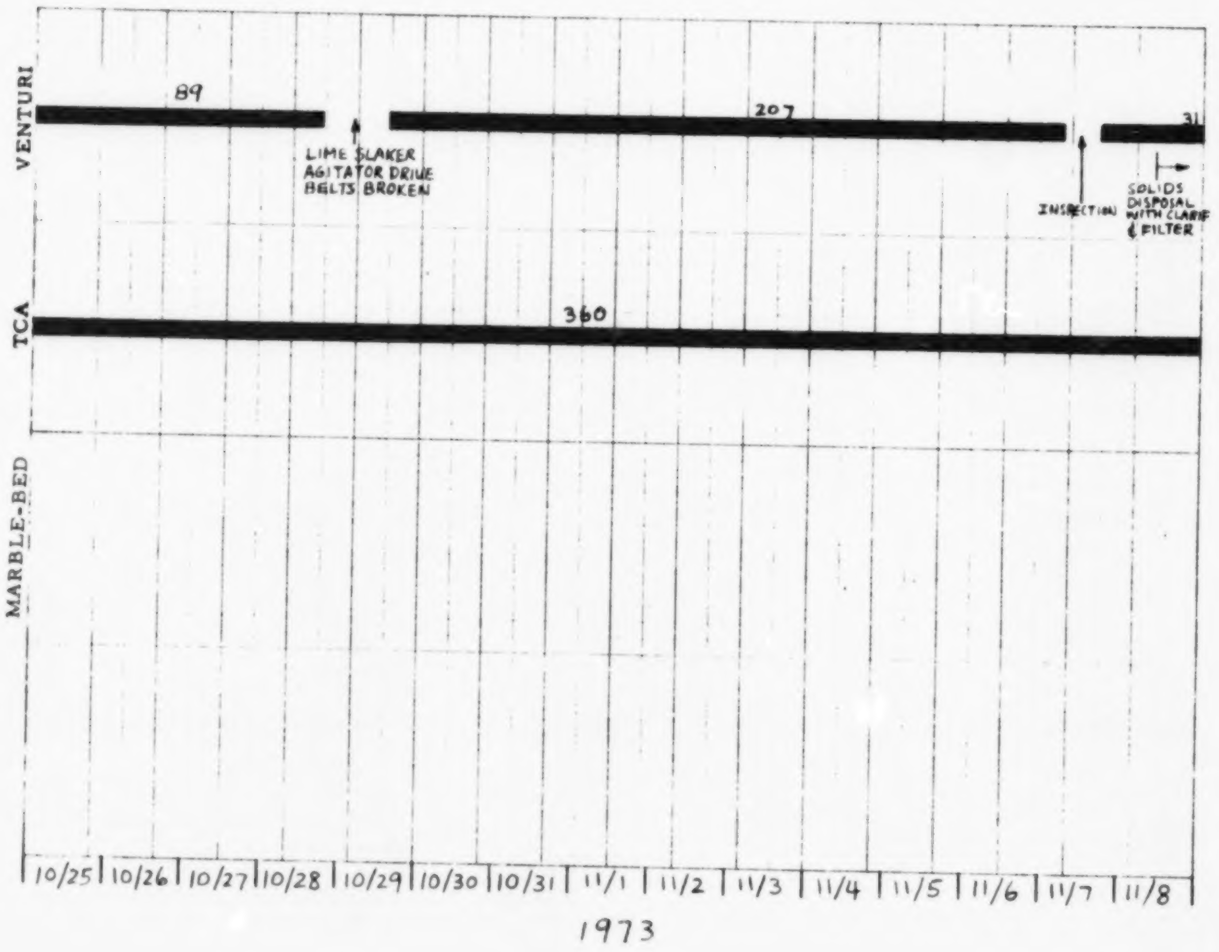

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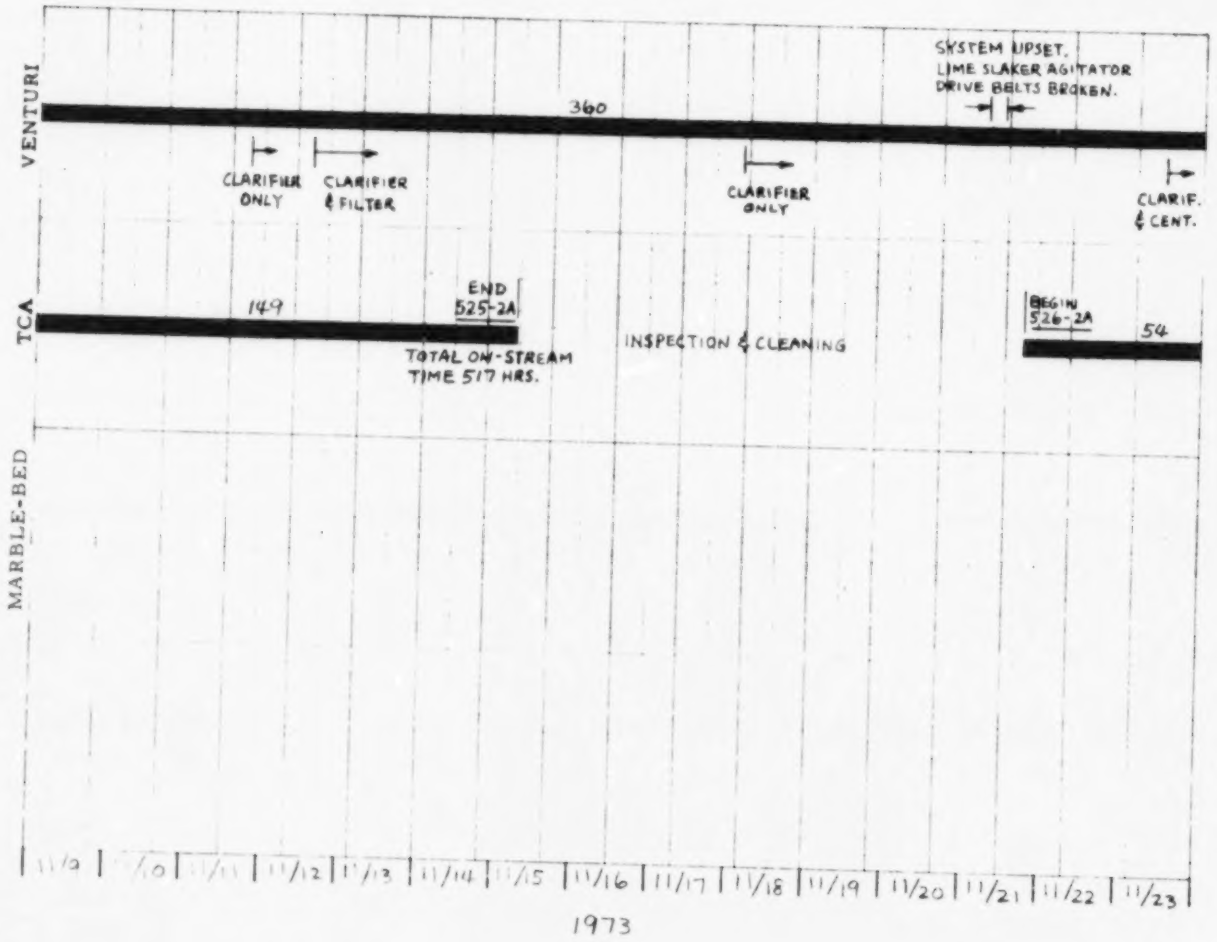

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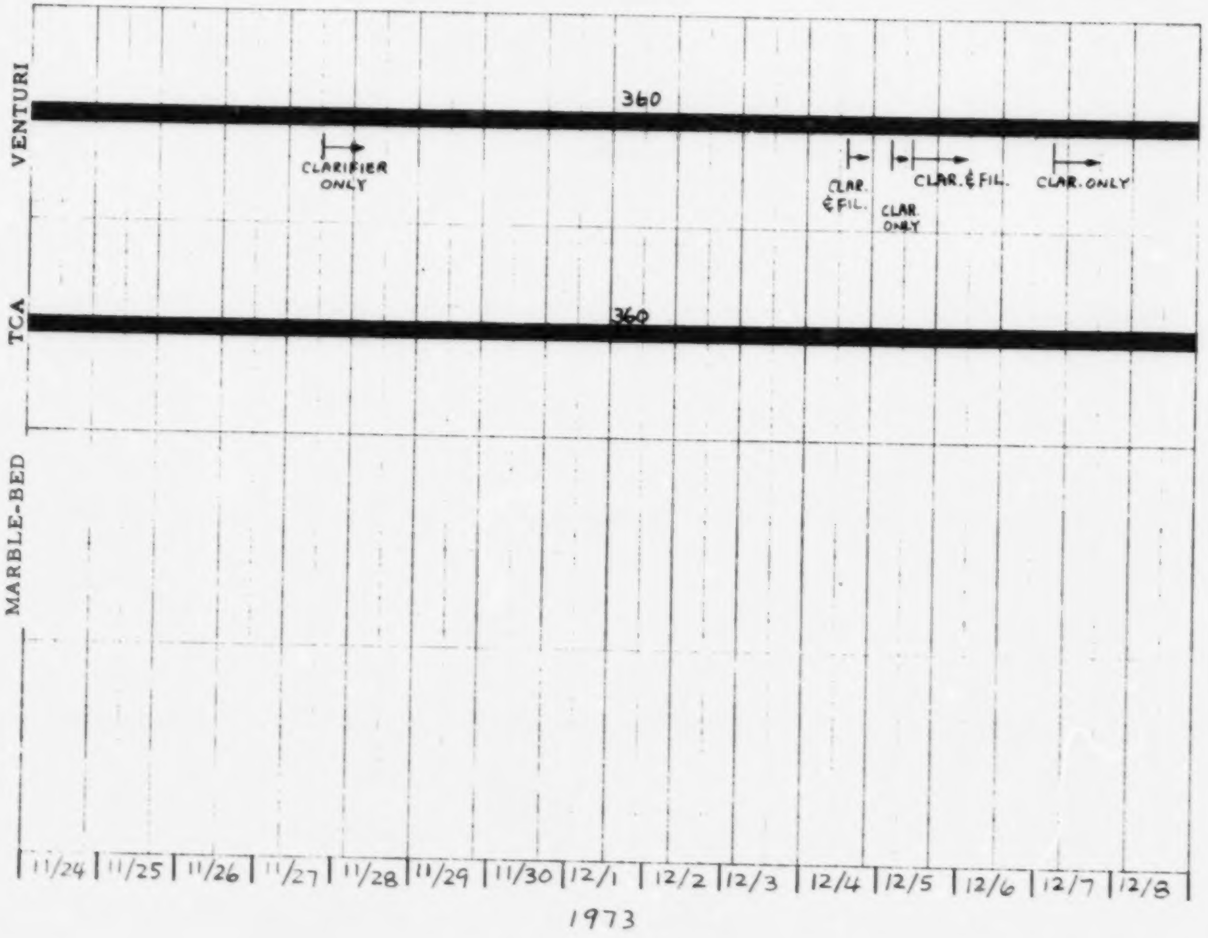

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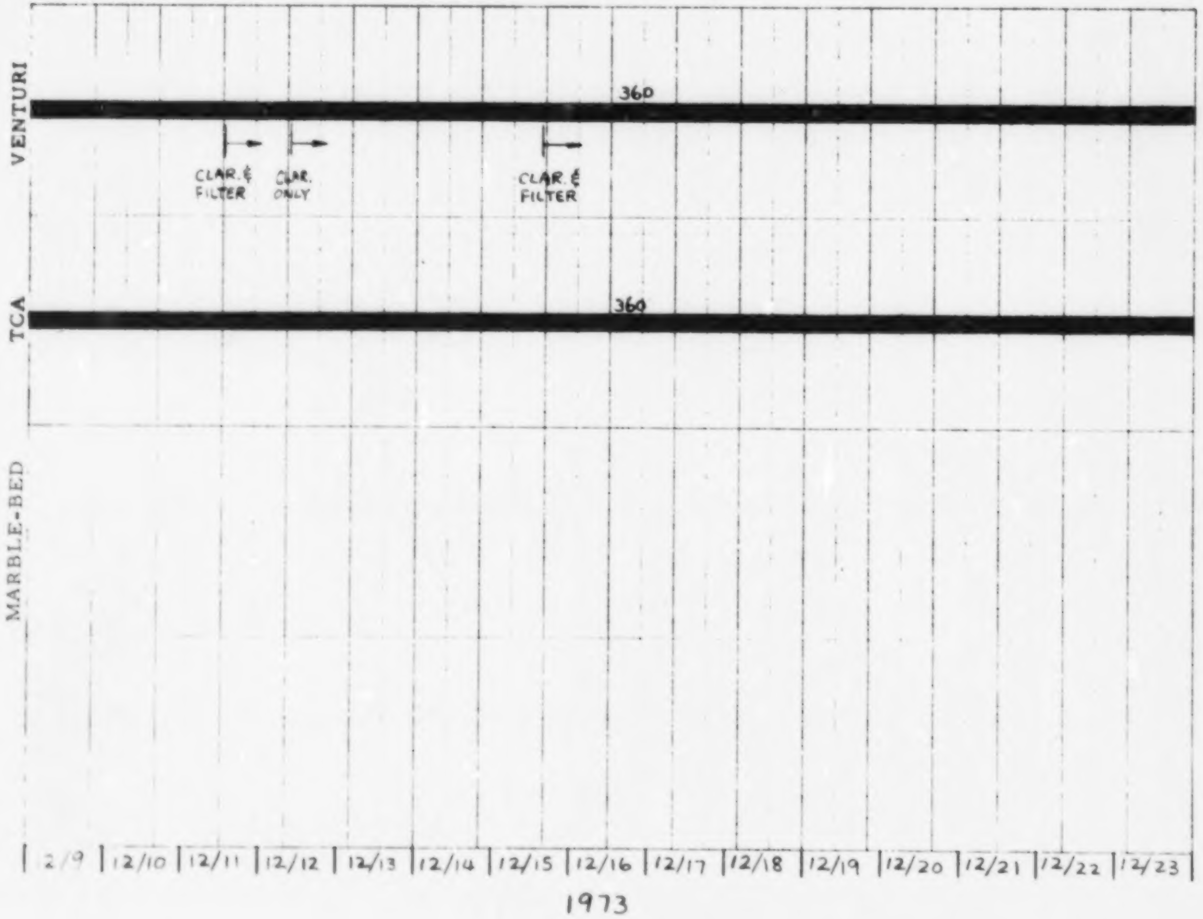

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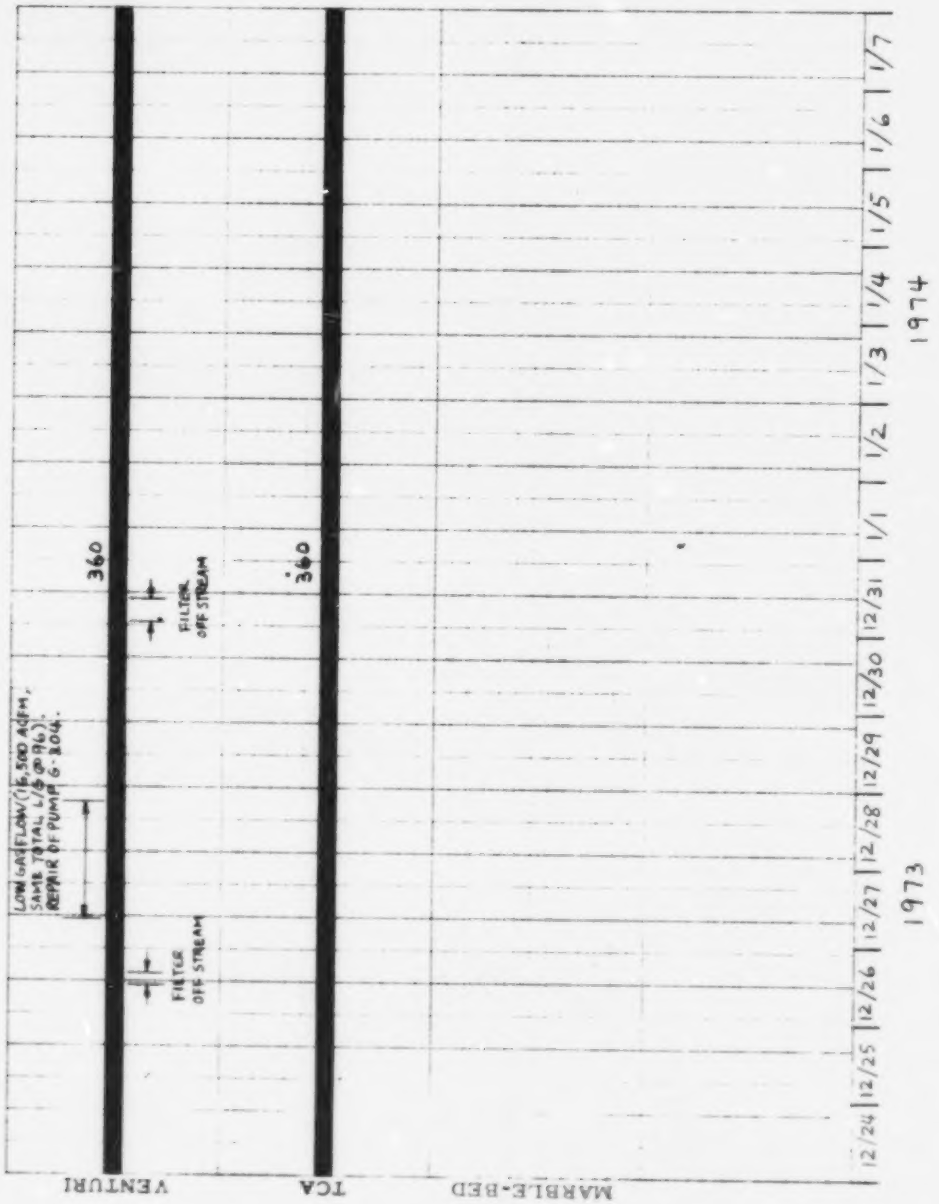

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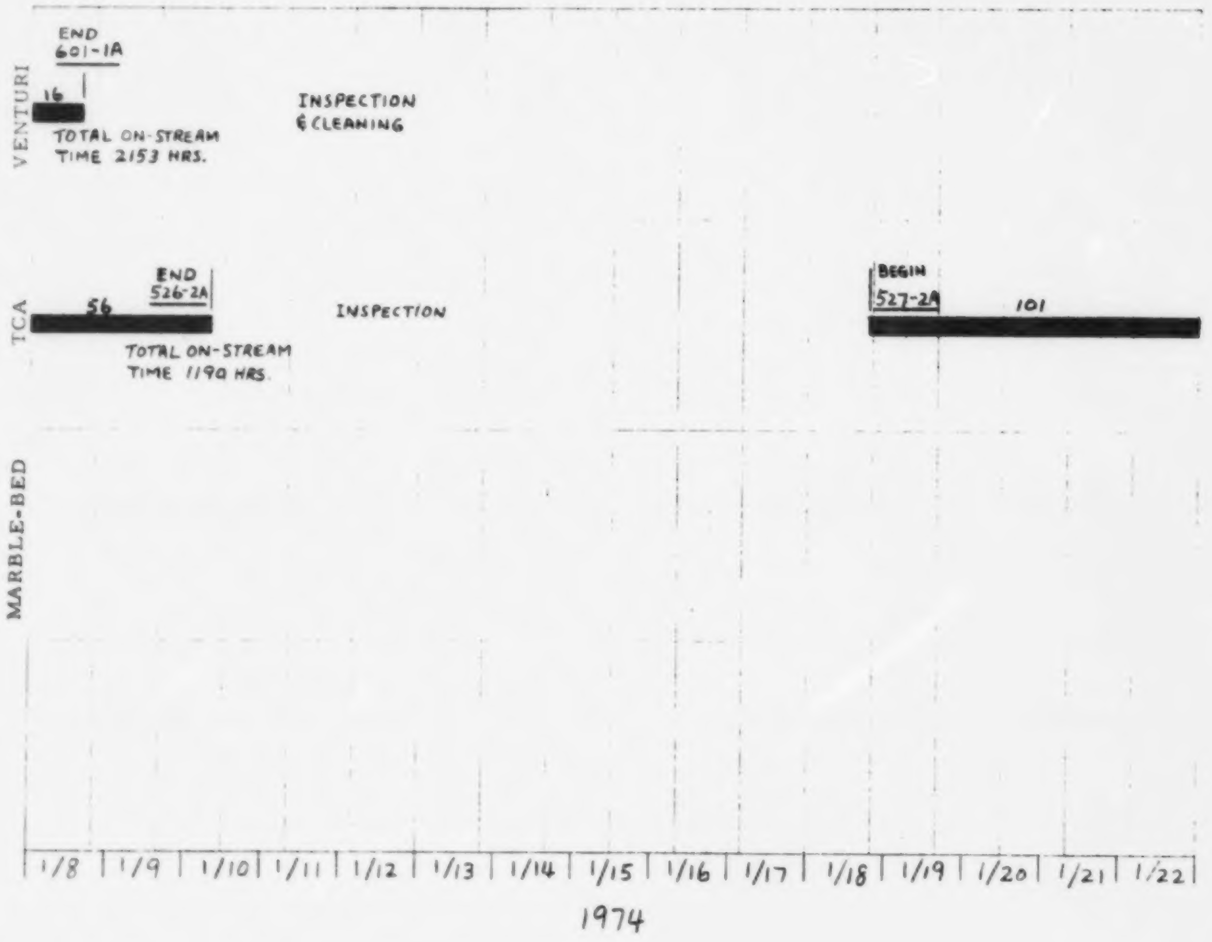

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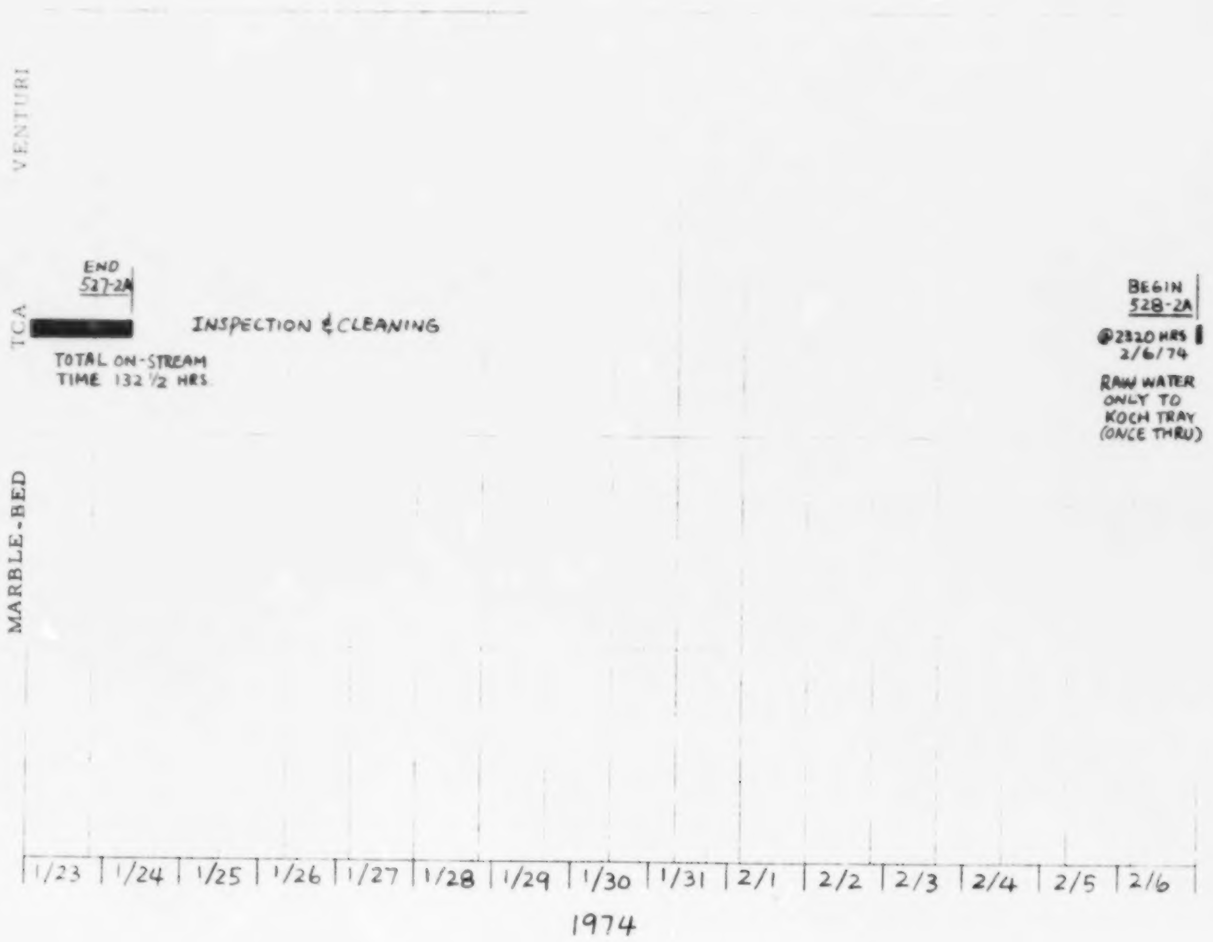

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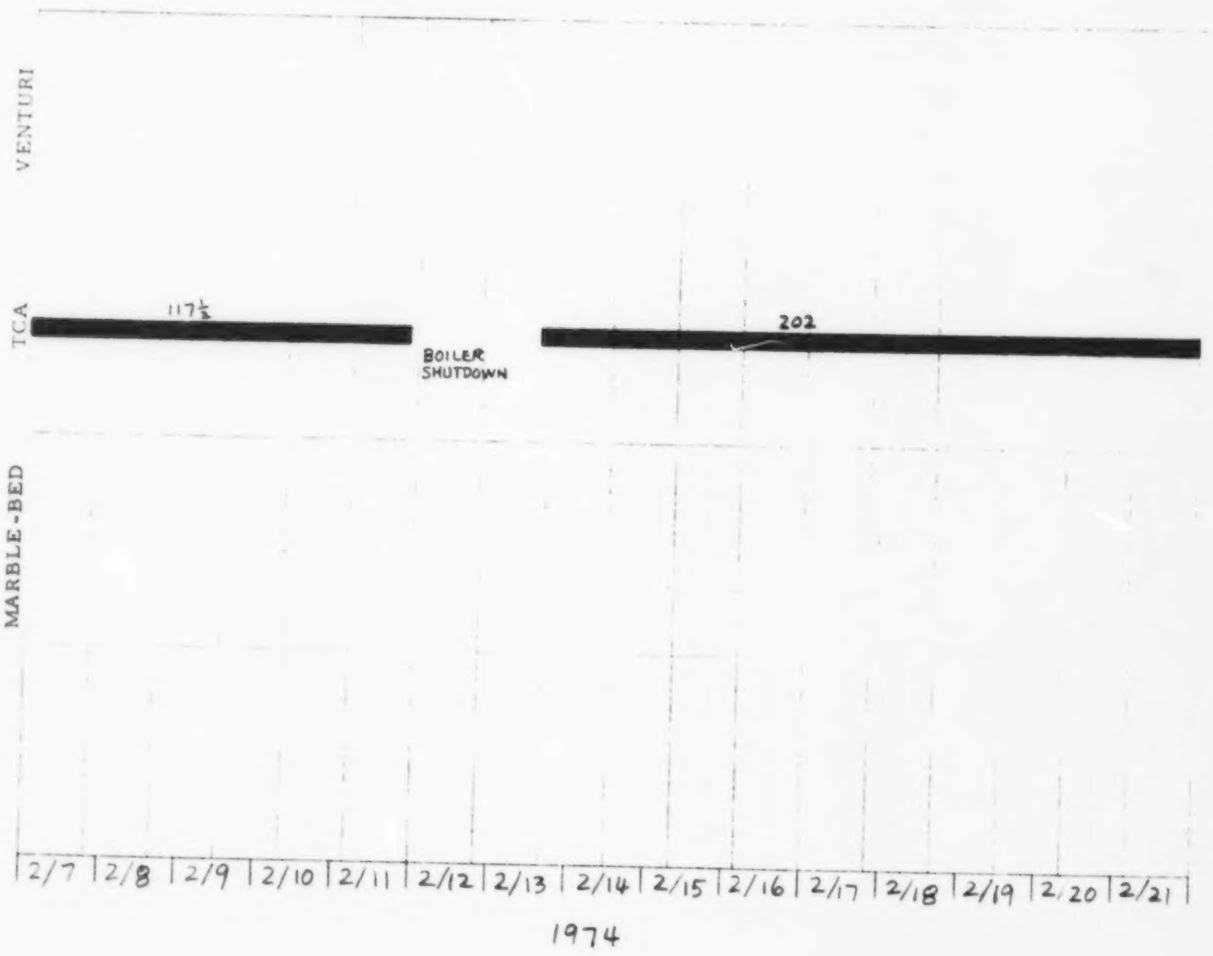

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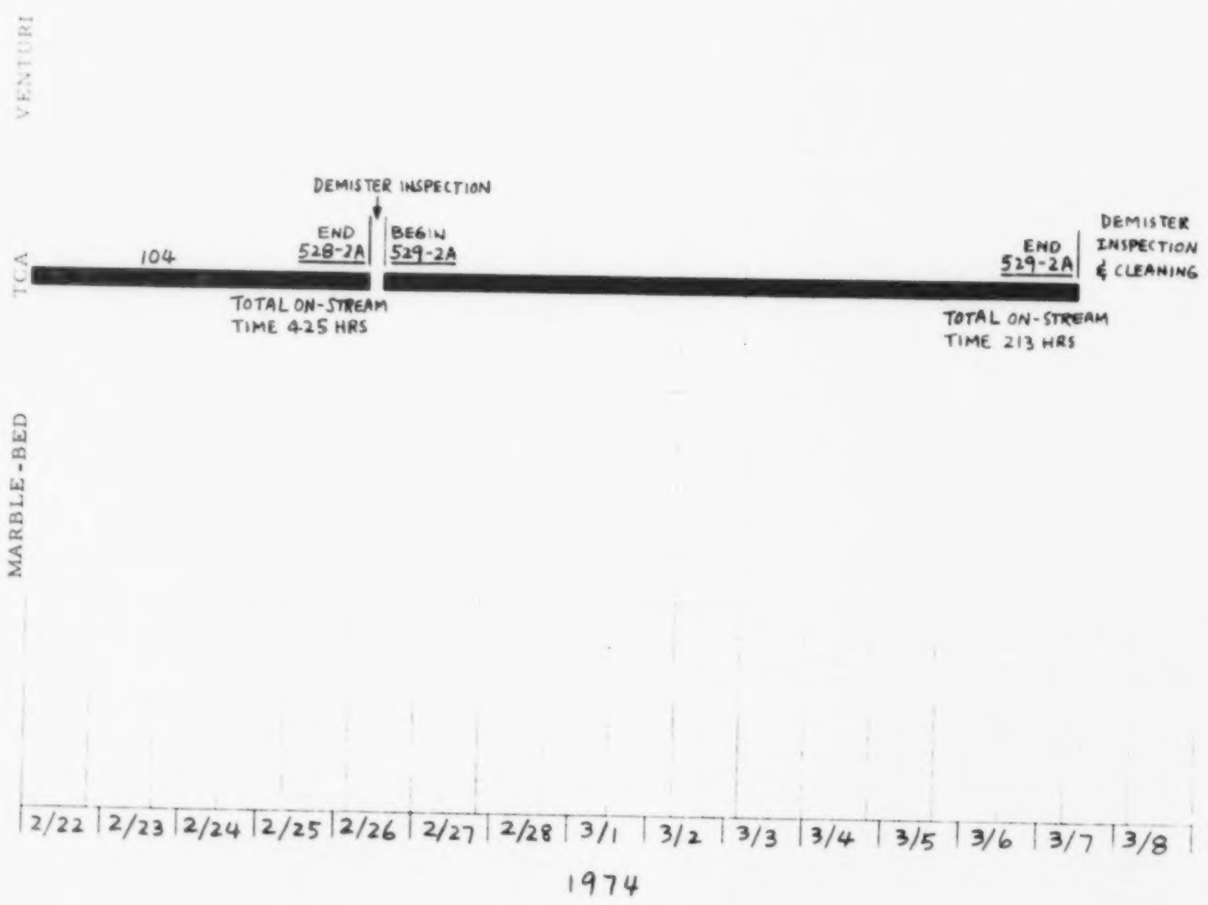

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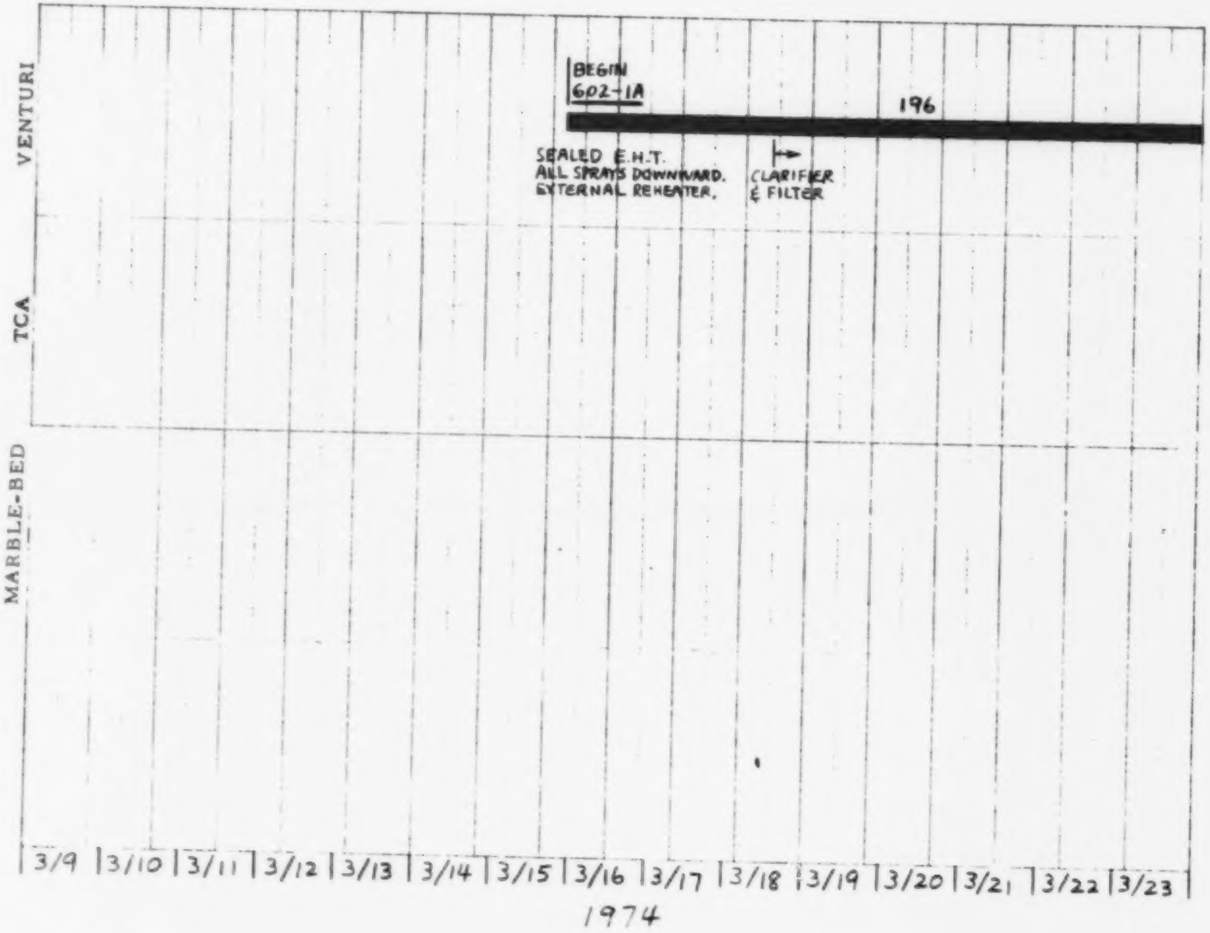

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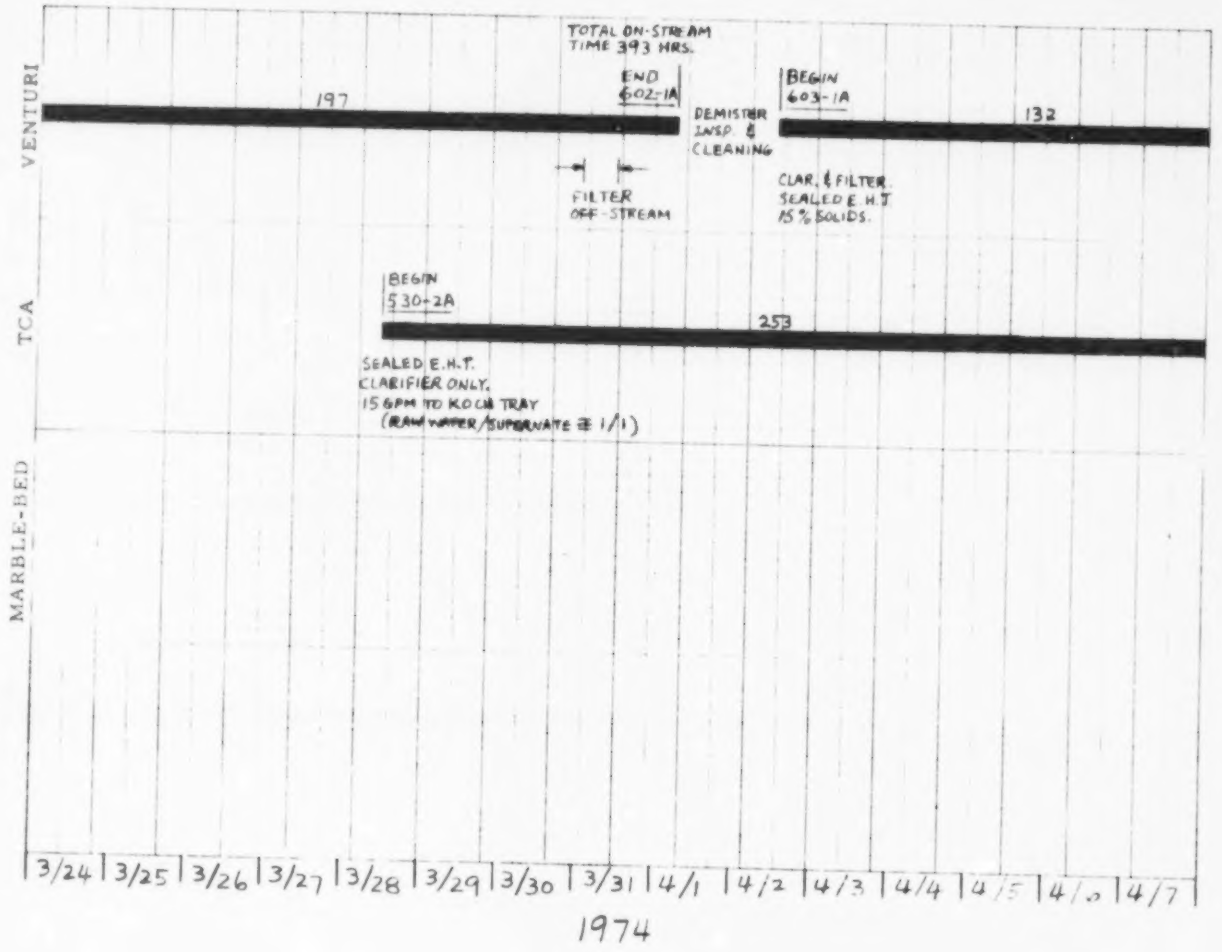

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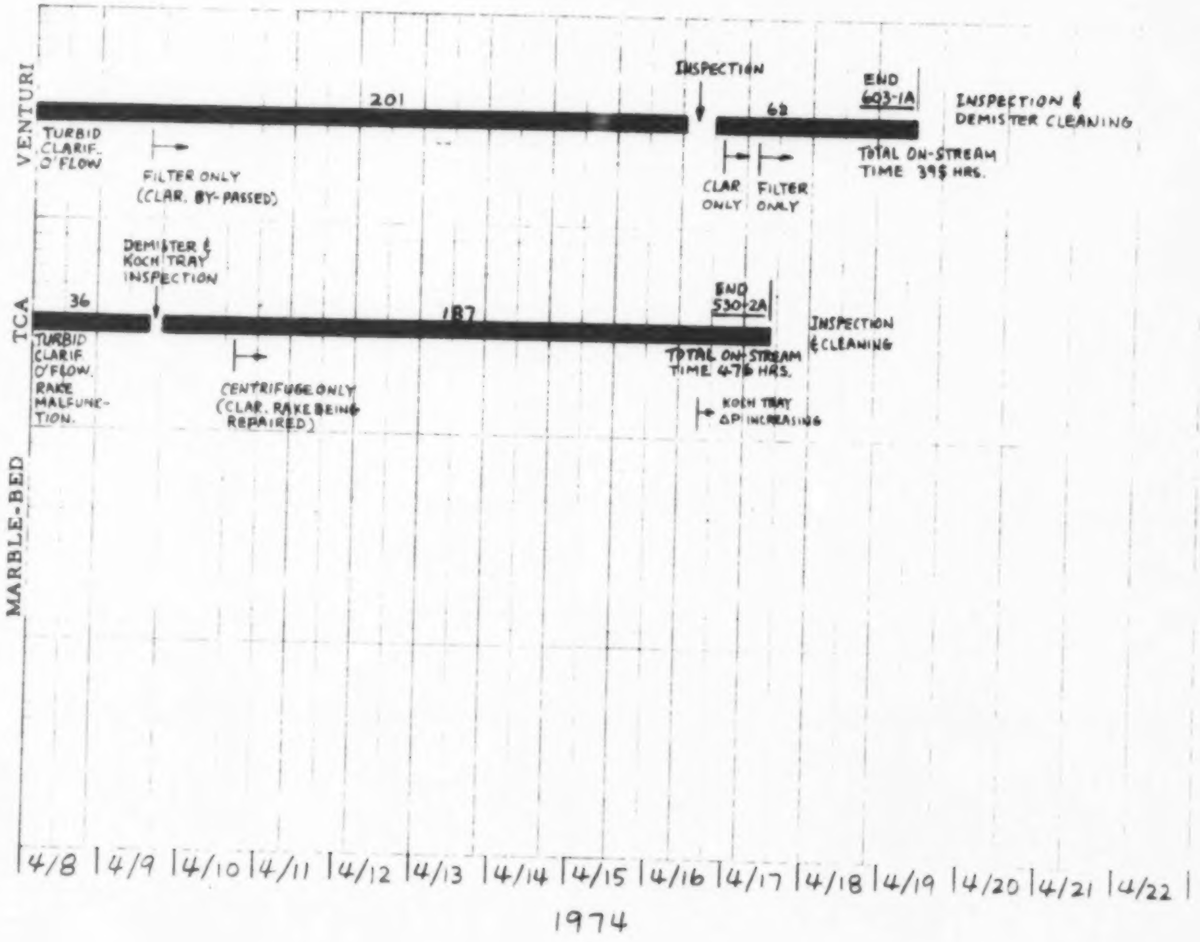

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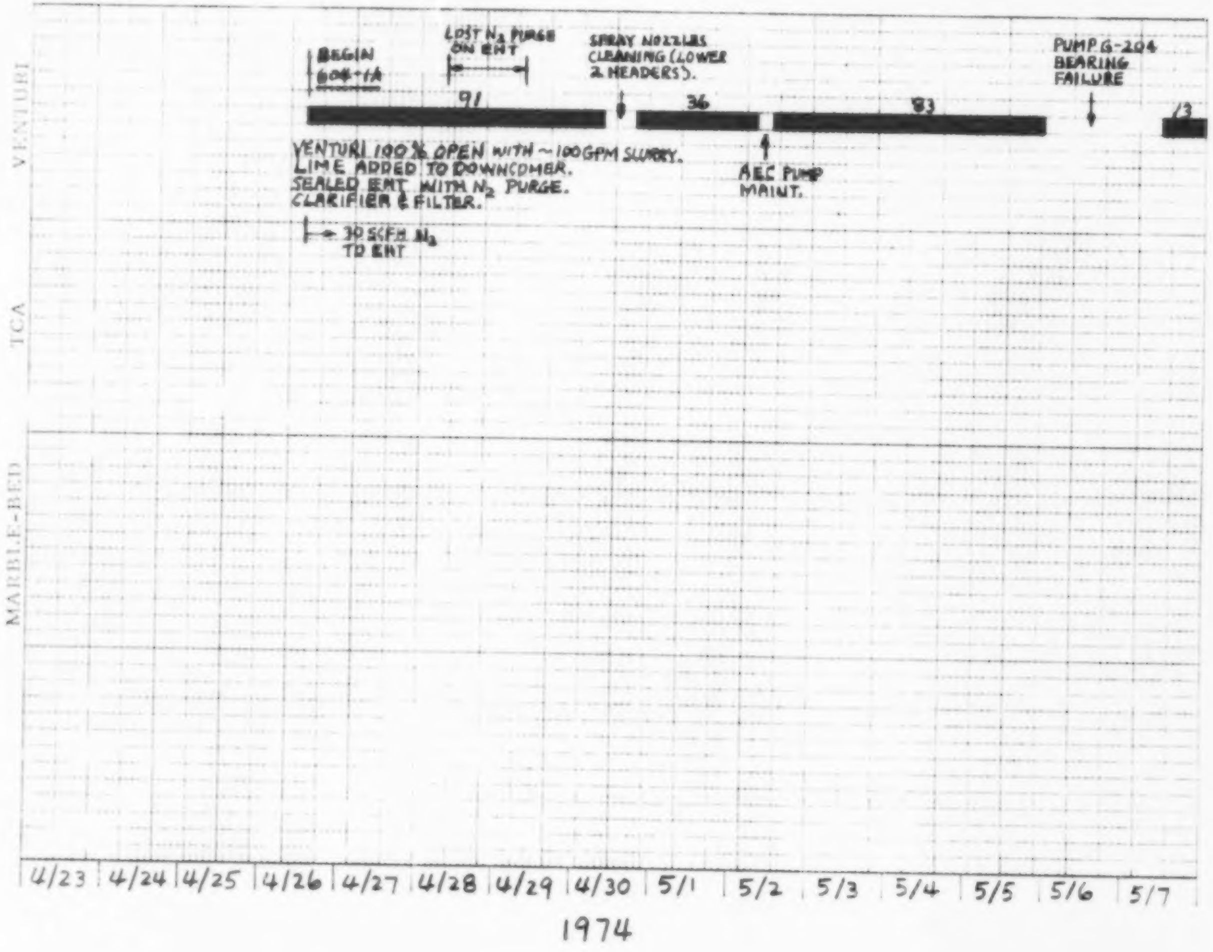

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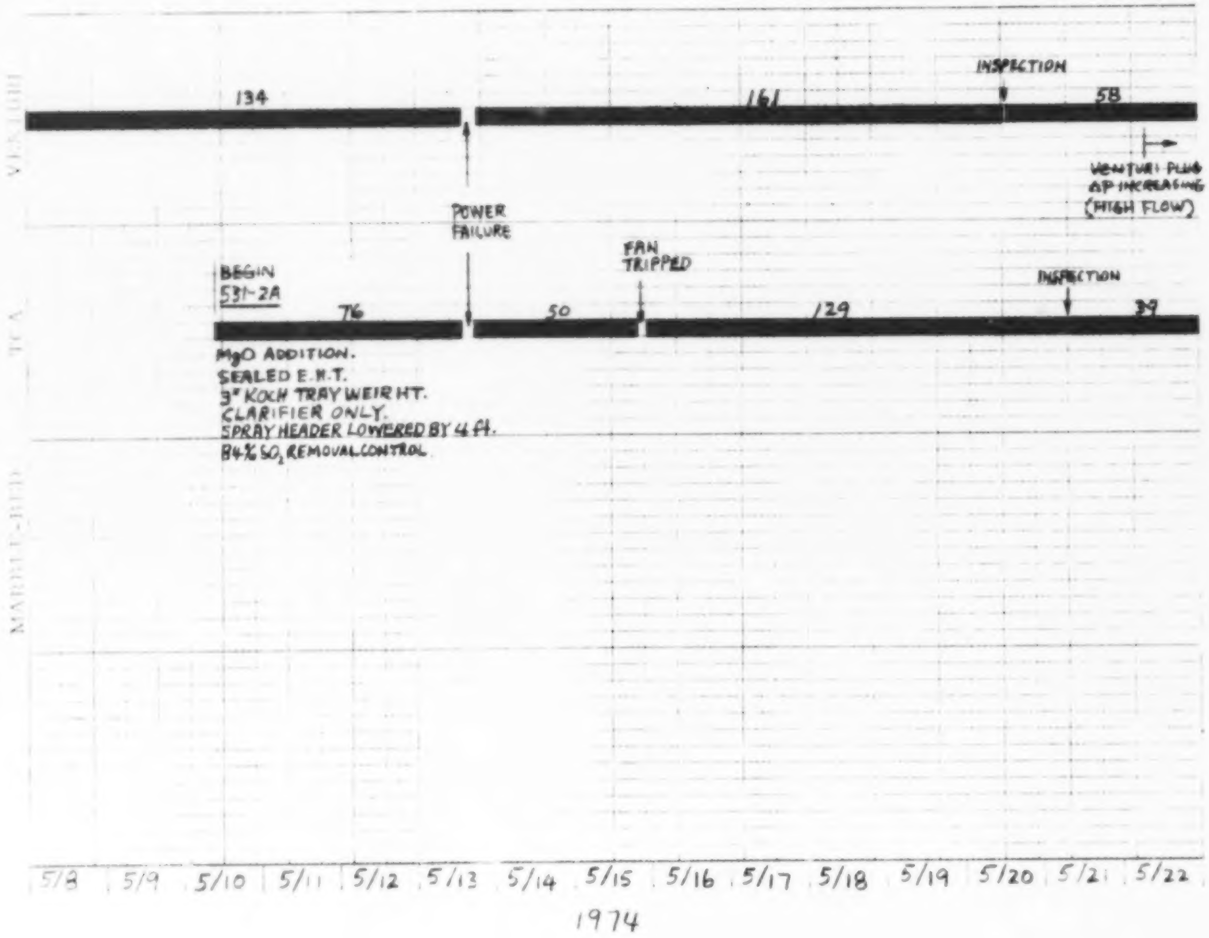

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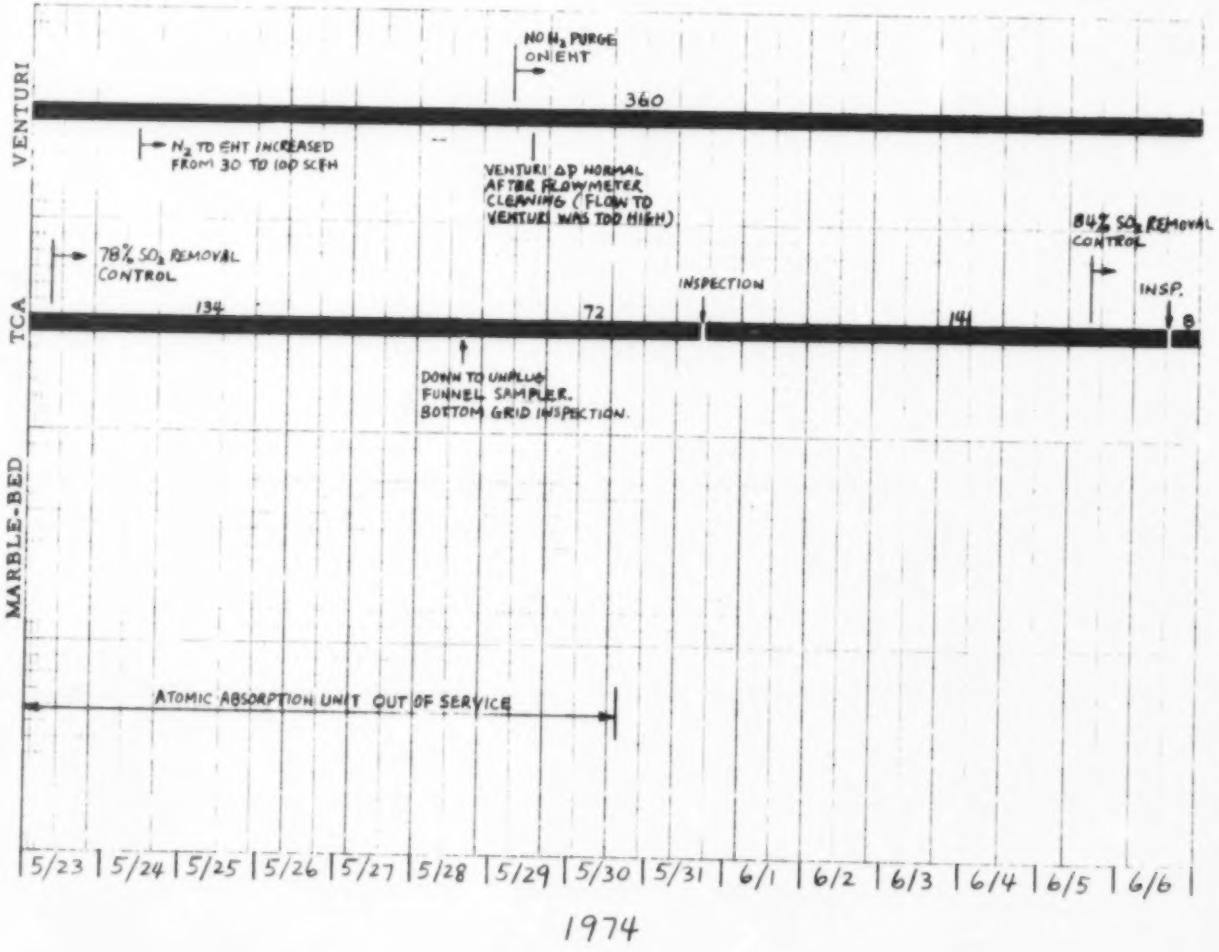

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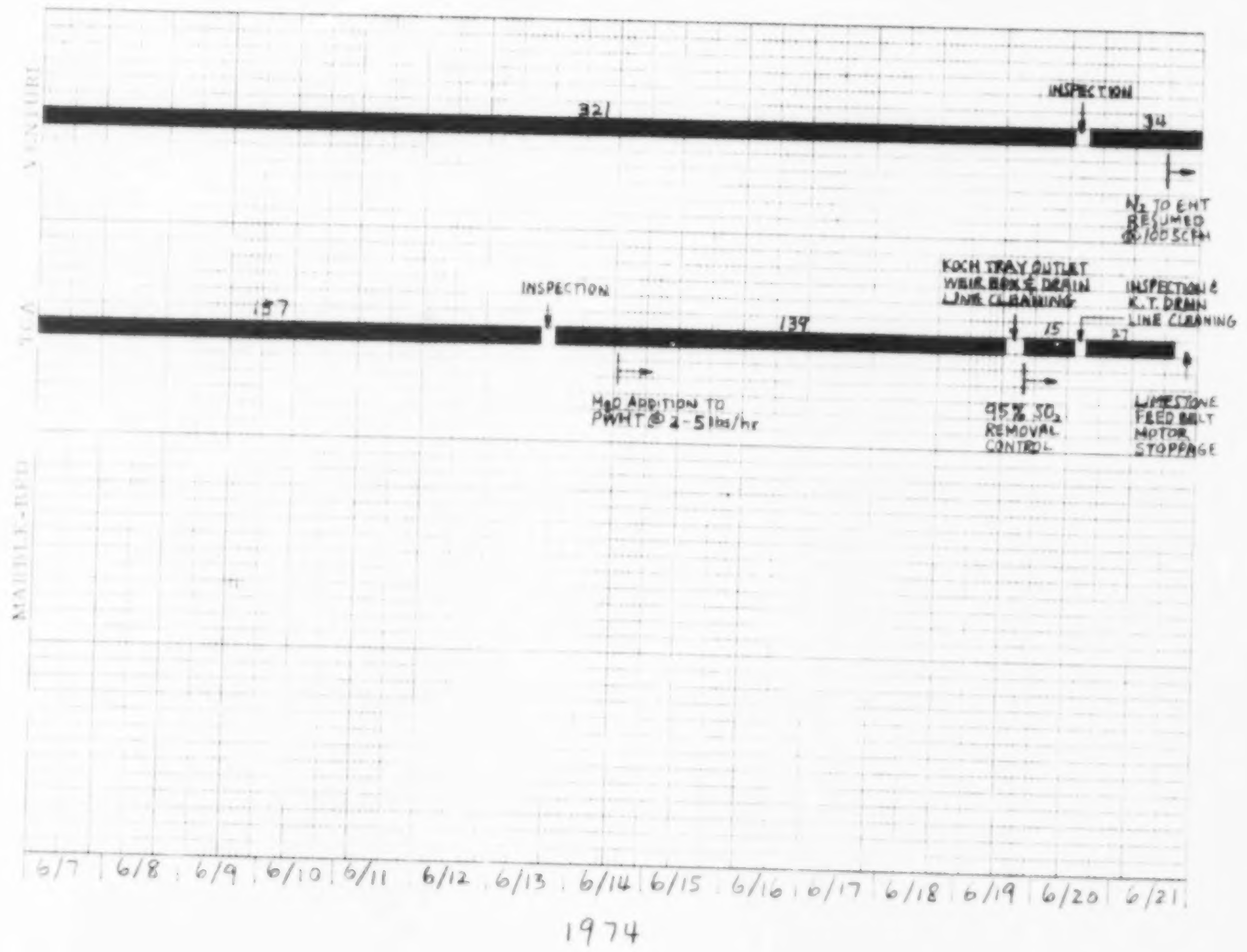

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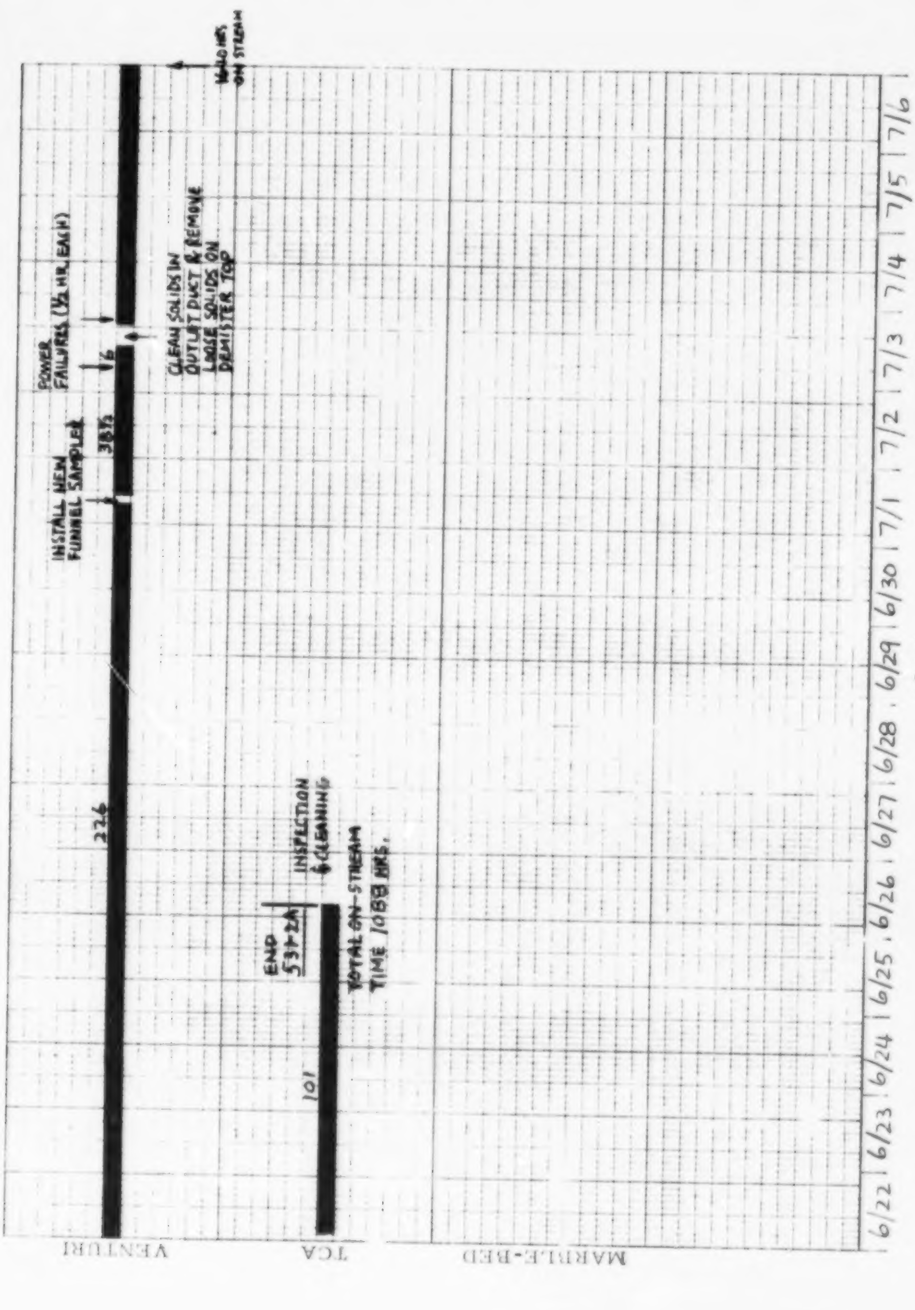

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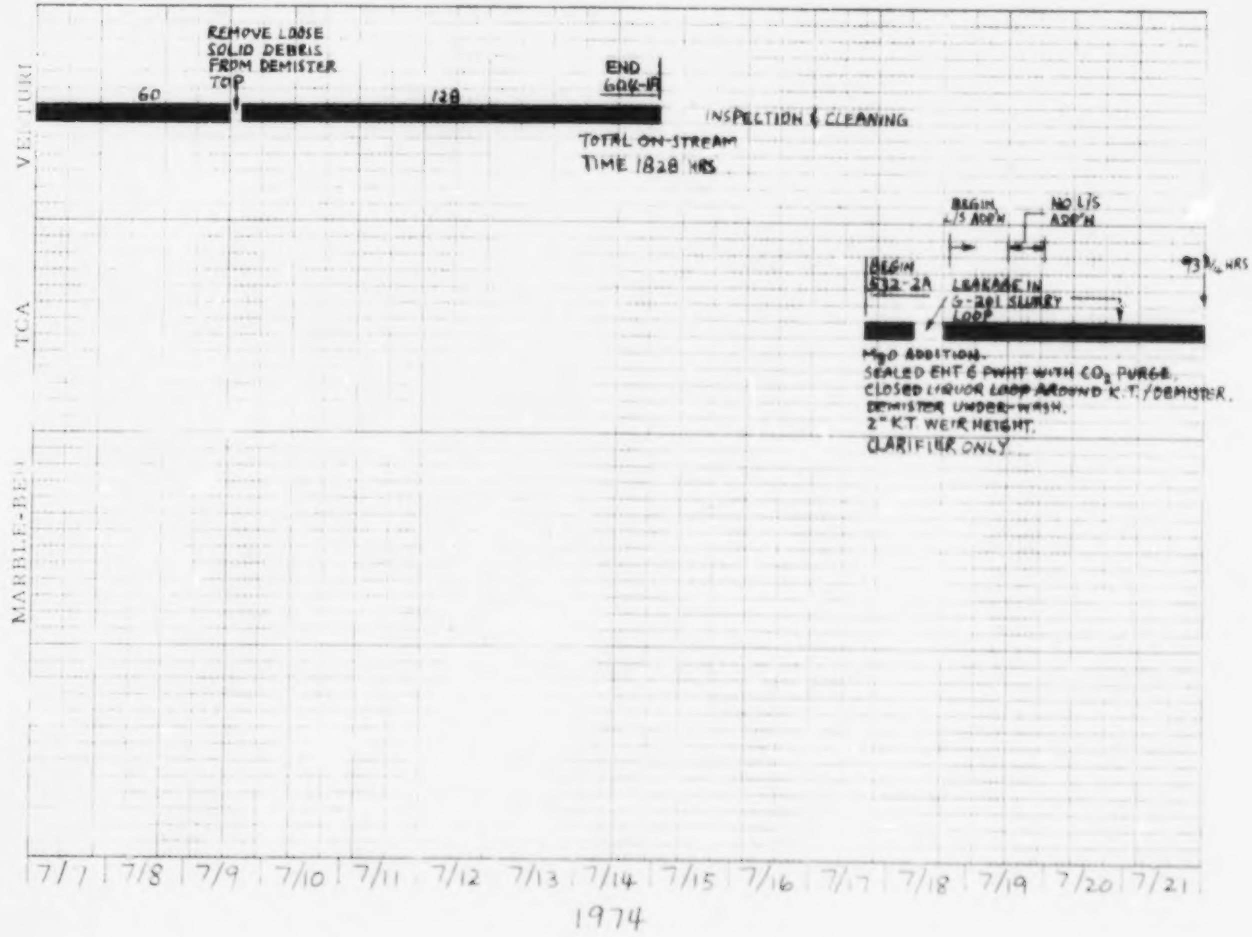

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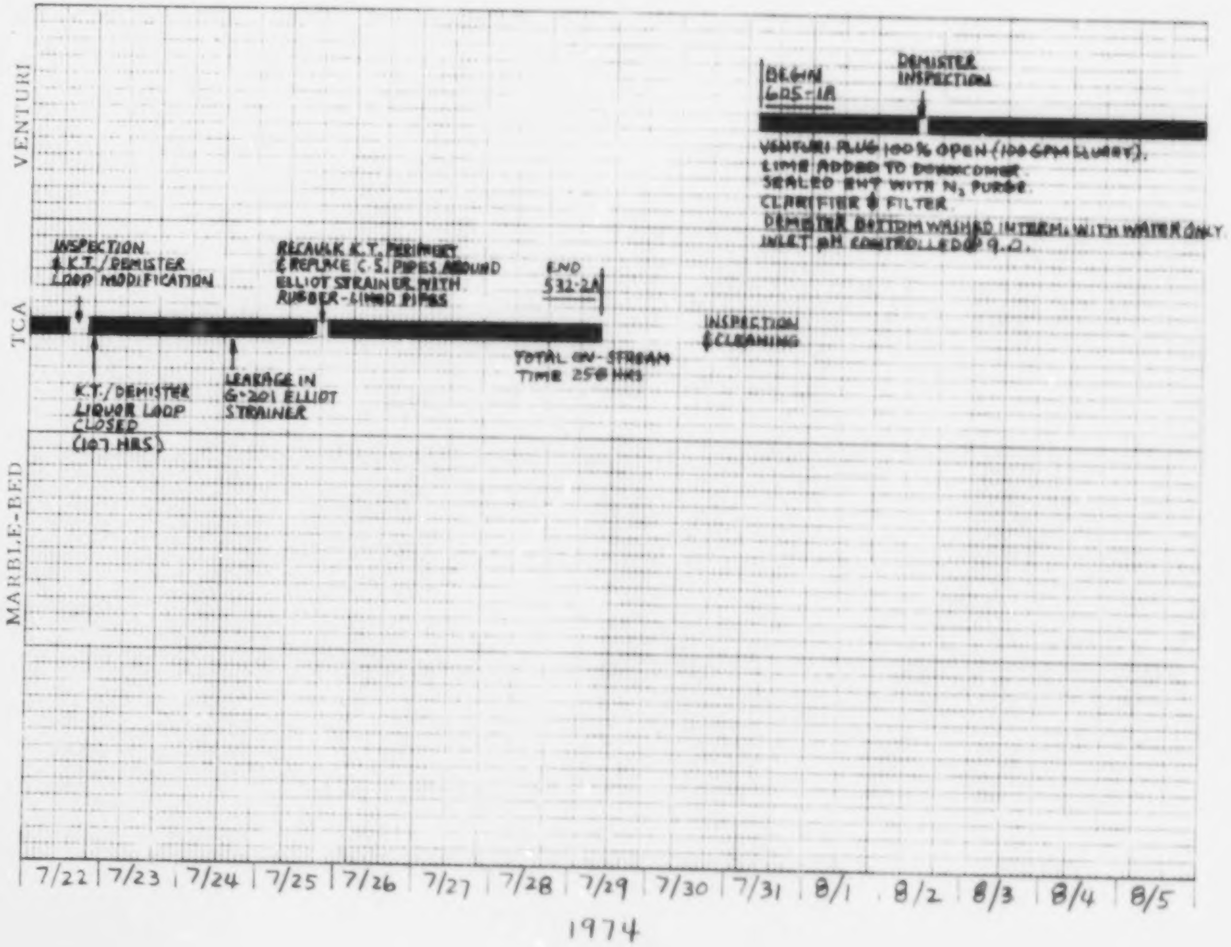

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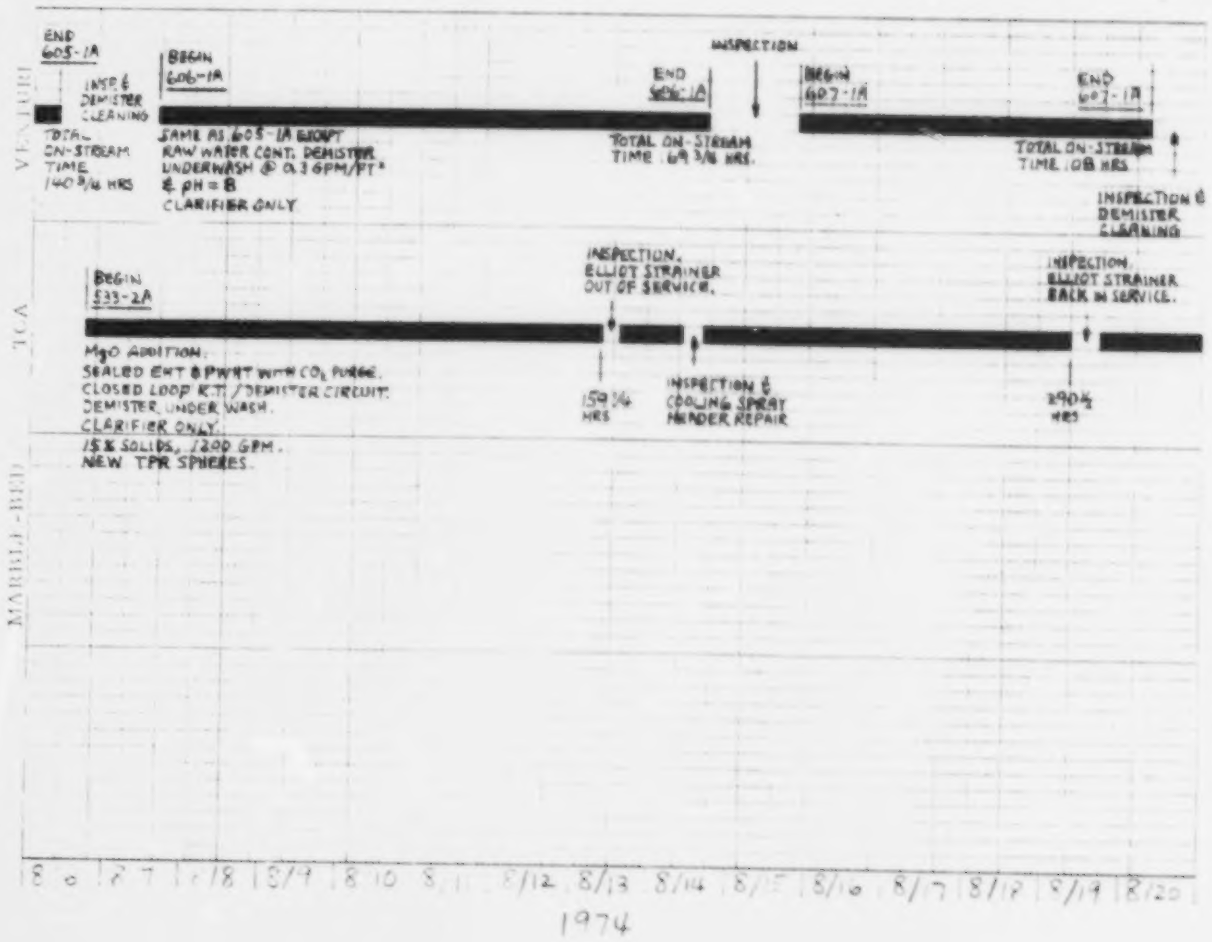

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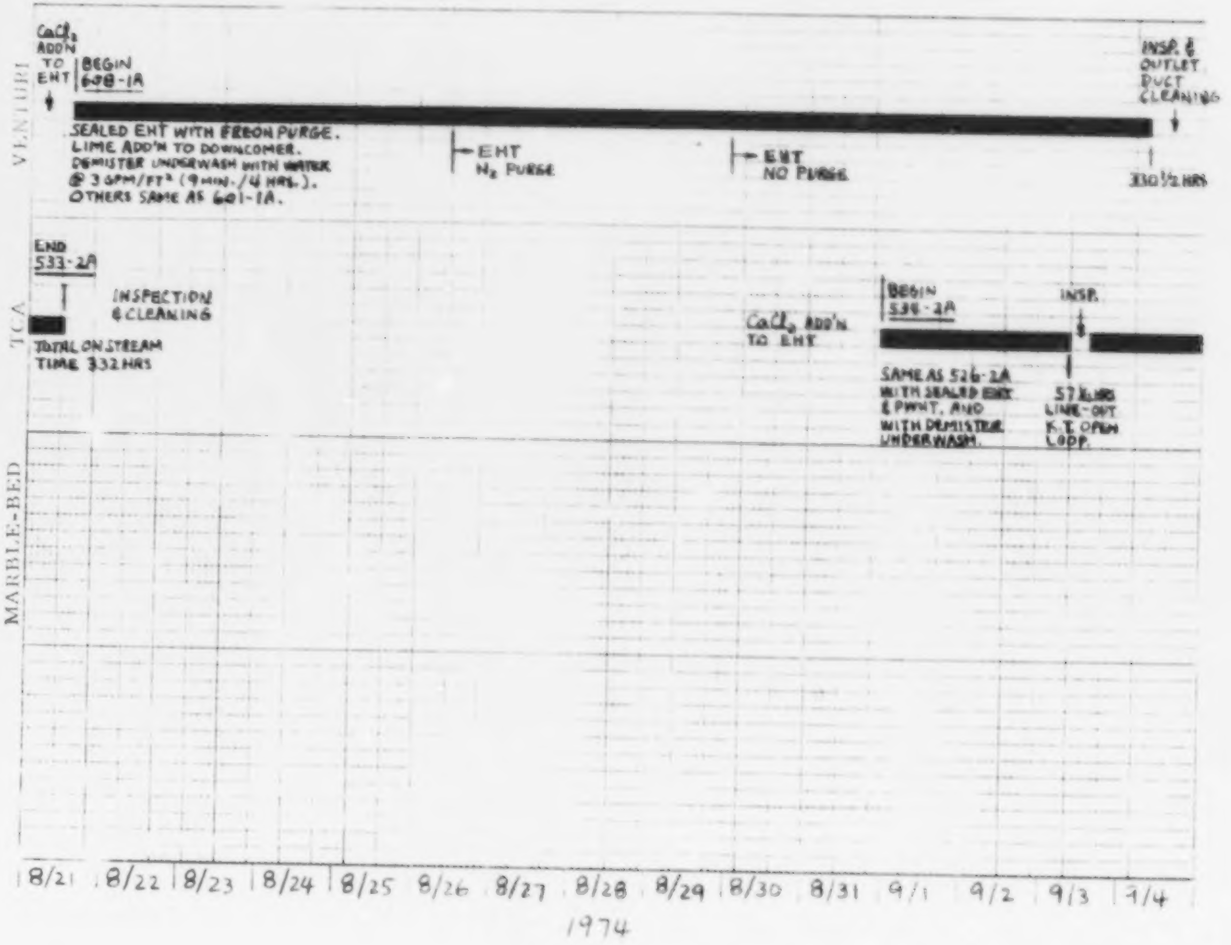

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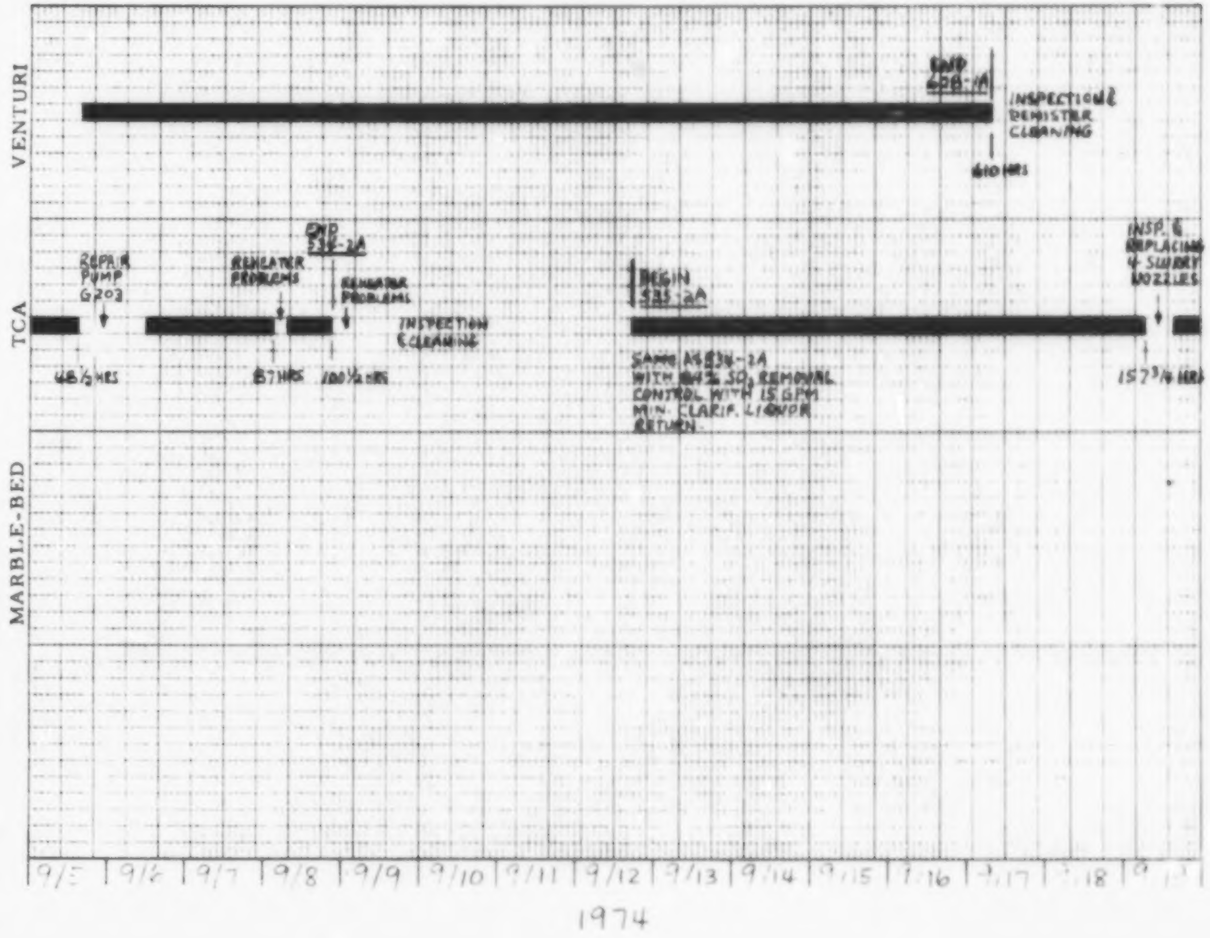

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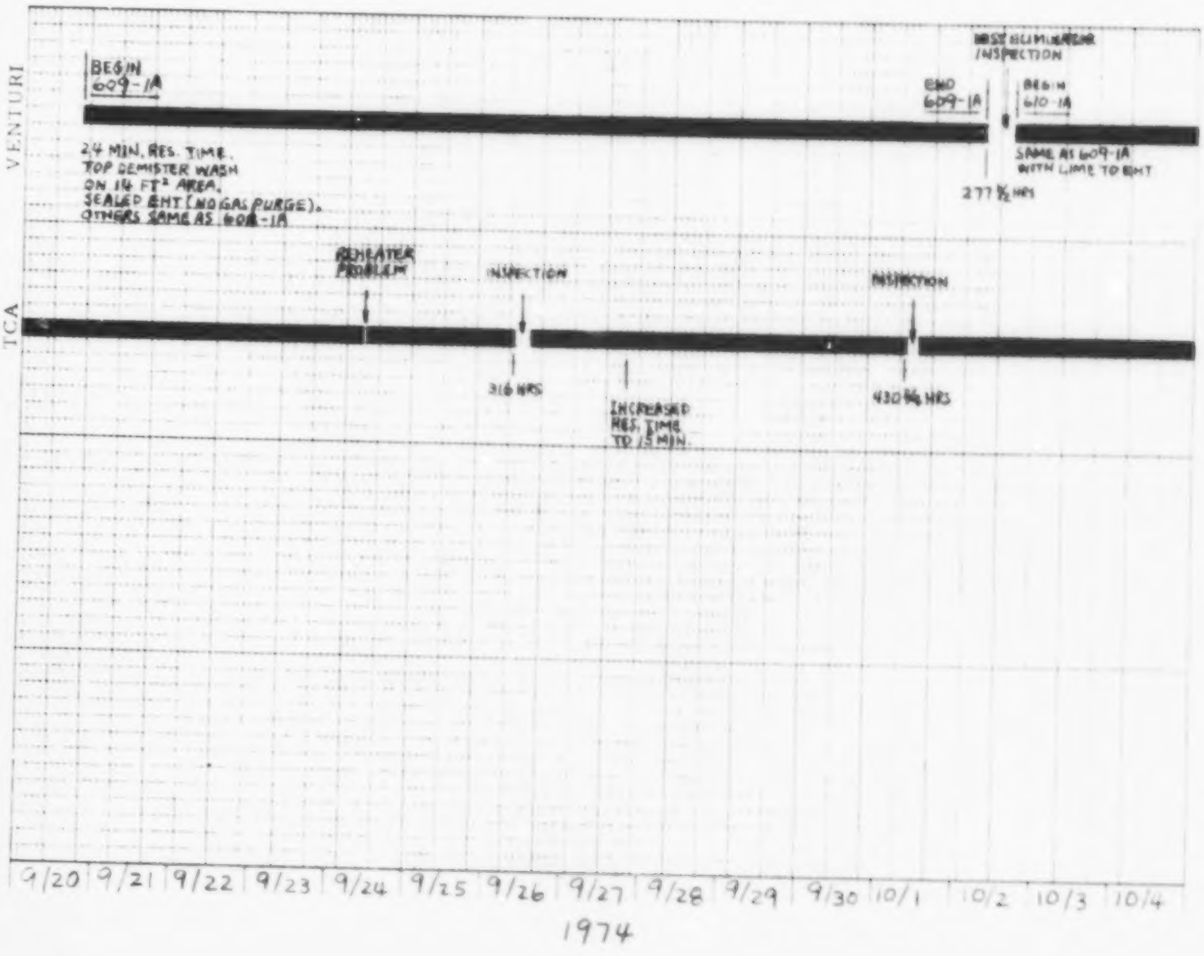

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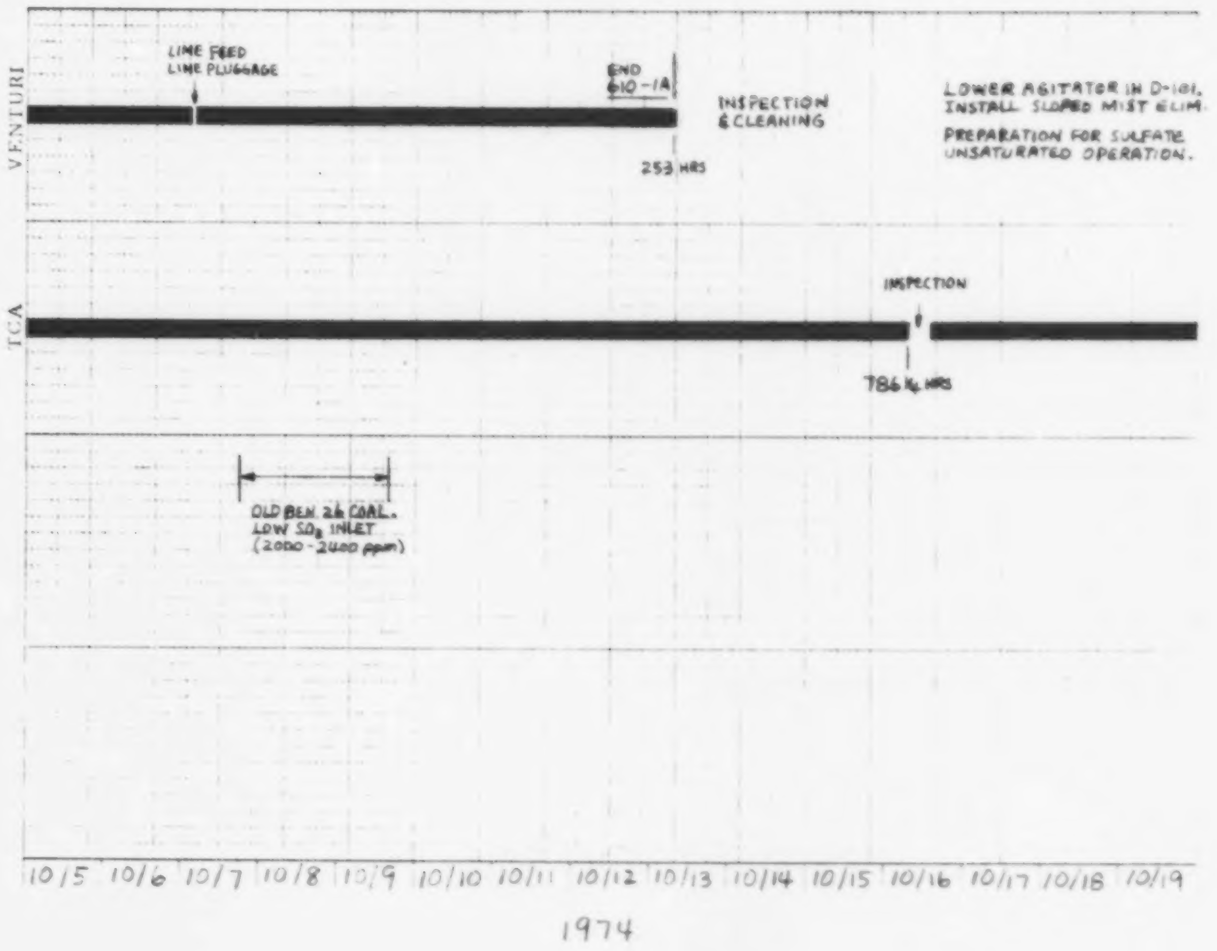

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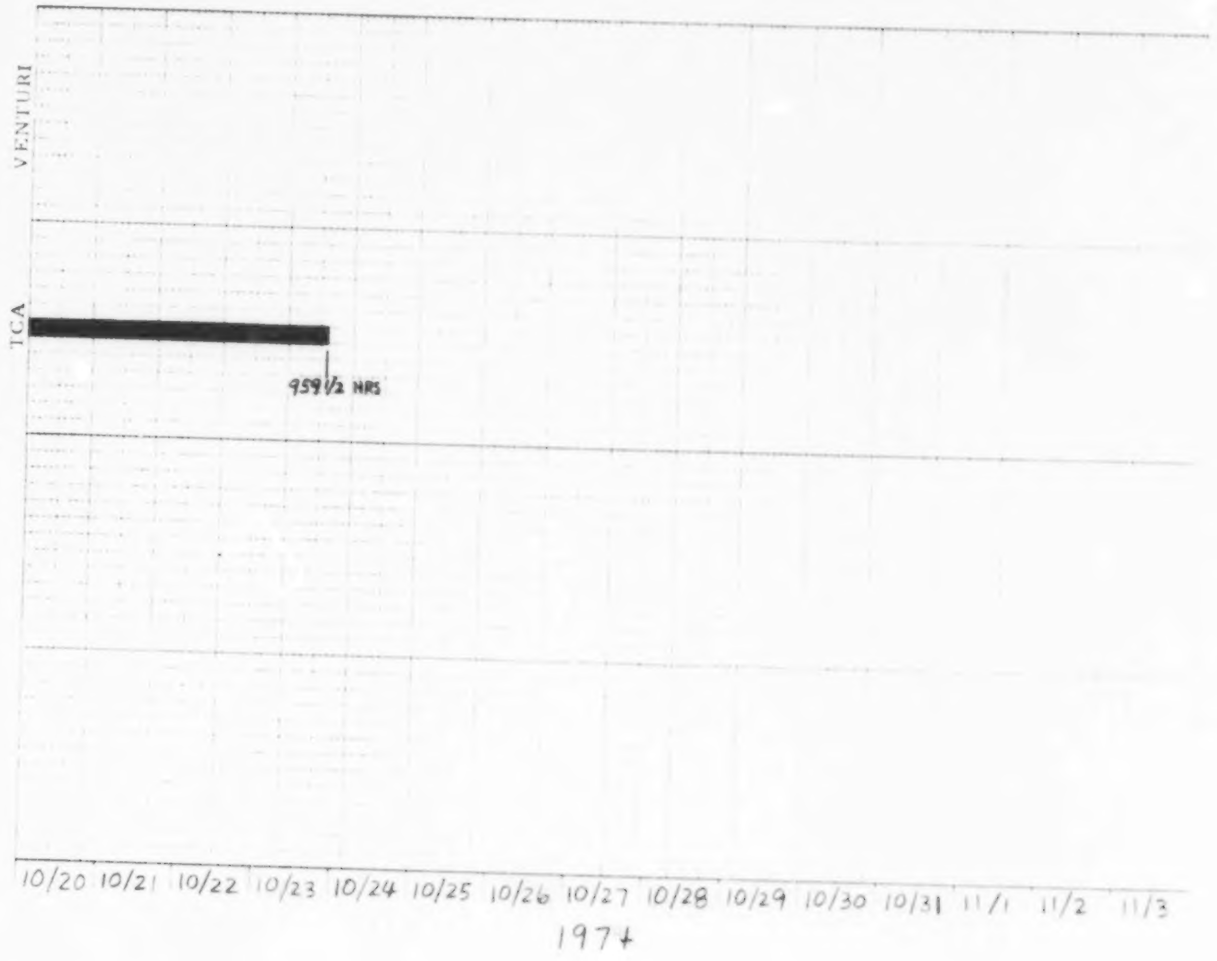

Appendix C

PROPERTIES OF RAW MATERIALS USED DURING THE TEST PROGRAM

Listed in this appendix are typical properties of the coal, alkaline feeds, and makeup water used in this test program.

COAL

Supplier: Old Ben Coal Co., Benton, Illinois

May 1972 through September 1973:

Type: Old Ben Mine 24

Analysis:	8.3	to	12.4	wt % total moisture
	3.0	to	4.5	wt % sulfur
	0.18	to	0.37	wt % chloride
	15.8	to	20.7	wt % ash

Approximate Ash Analysis:

50 wt % SiO_2
18 wt % Al_2O_3
16 wt % Fe_2O_3
7 wt % CaO
1 wt % MgO
1 wt % SO_3
2 wt % K_2O
1 wt % Na_2O
3 wt % Ignition loss

October 1973 through October 1974:

Type: Mixture of Old Ben Mines 24 and 26 either straight from mines or reclaimed from plant coal storage pile

Analysis:	9.4	to	13.4	wt % total moisture
	2.3	to	5.5	wt % sulfur
	0.03	to	0.27	wt % chloride
	14.7	to	27.9	wt % ash

Approximate Ash Analysis:

54 wt % SiO_2
23 wt % Al_2O_3
12 wt % Fe_2O_3
3 wt % CaO
1 wt % MgO
1 wt % SO_3
3 wt % K_2O
1 wt % Na_2O
3 wt % Ignition loss

SODIUM CARBONATE

Supplier: Vol-State Chemical Co., Chattanooga, Tennessee
Type: Soda ash, Grade 58 % light
Analysis: 58 wt % as Na_2O

LIMESTONE

Supplier: Fredonia Quarries, Fredonia, Kentucky,

August 1972 through July 1973:

Type: Fredonia Valley Blue White
Analysis: 90 wt % $CaCO_3$
5 wt % $MgCO_3$
5 wt % Inerts
Nominal Grind:
90 wt % less than 325 mesh
81 wt % less than 30 microns
74 wt % less than 20 microns
48 wt % less than 6 microns

July 1973 through October 1974:

Type: Fredonia Valley White

Analysis: 95 wt % $CaCO_3$
1 wt % $MgCO_3$
4 wt % Inerts

Nominal Grind:
97 wt % less than 325 mesh
92 wt % less than 30 mocrons
86 wt % less than 20 microns
53 wt % less than 6 microns

LIME

Supplier: Linwood Stone Co., Davenport, Iowa

Type: Pebble lime, unslaked

Analysis: 97.0 wt % CaO total
95.5 wt % CaO available
0.28 wt % MgO
0.47 wt % Inerts

MAGNESIUM OXIDE

Supplier: Basic Chemicals, Ft. St. Joe, Florida

Type: MAGOX PG (pollution grade)

Analysis: 97.6 wt % MgO
1.5 wt % CaO
0.5 wt % SiO_2
0.4 wt % R_2O_3

MAKEUP WATER

Source: Ohio River (filtered)

Typical Analysis:
pH = 7.8
Conductivity = 190 micromhos/cm

Species	ppm, wt
Ca	45
Mg	3
Na	22
K	3
Mo	1.5
Al	0.9
Fe	0.6
Mn	0.06
Cr	0.04
$SO_4^{=}$	10
CO_3	18
Cl^-	177

Appendix D

TABULAR LISTING OF AIR/WATER AND SODIUM CARBONATE TEST DATA

D.1 PRESSURE DROP DATA FROM AIR/WATER AND SODIUM CARBONATE TESTS

The pressure drop data for the air/water and sodium carbonate runs for the three scrubber systems are shown in Tables D-1 through D-9. The "total" pressure drops refer to pressure drops from the point of gas entrance to the gas humidification sections to the point of gas exit downstream from the mist eliminators and their associated wash headers.

The observed variations in the independent and dependent variables for the presented air/water and sodium carbonate (soda-ash) runs were:

Gas flow rate	±200 cfm
Liquor flow rate	±10 gpm
Marble-Bed turbulent layer height	±20%
Total pressure drop	±3%
Mist Eliminator pressure drop	±8%

As can be seen from Tables D-1 through D-9, the replicate runs were all in agreement to within the estimated experimental variations of pressure drop.

Table D-1

PRESSURE DROP DATA FROM AIR/WATER RUNS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Water Flow Rate, gpm		Water Temperature, °F	Plug Position, % Open	Pressure Drop, in. H_2O			Replicate Runs
				Venturi	Spray Tower			Total	Venturi	Mist Elim.	
5/20	101-1B	23,000	89	0	390	67	25	6.6	4.6	.97	A
5/20	103-1B	13,100	88	0	0	-	50	1.5	.8	.34	
5/20	111-1A	9,600	86	0	200	66	100	.7	.2	.16	
5/20	119-1A	23,000	96	0	0	-	100	2.9	.9	.98	
5/20	102-1B	8,700	91	405	395	67	75	1.6	1.2	.13	
5/21	104-1A	17,700	87	200	200	66	100	3.0	1.4	.54	
5/21	110-1A	23,000	85	0	400	66	25	6.6	4.6	1.00	A
5/21	112-1A	8,300	87	0	0	-	25	.8	.7	.12	
5/21	108-1A	17,900	95	0	0	-	75	1.9	.8	.60	
5/21	109-1A	23,200	98	395	390	66	50	11.2	8.2	1.00	
5/21	107-1A	13,300	100	205	205	67	25	4.0	3.4	.30	
5/21	113-1A	13,300	100	400	395	67	100	2.5	1.6	.29	
5/21	115-1A	23,200	96	200	200	67	75	5.8	3.4	.90	
5/23	120-1A	8,300	87	0	210	68	100	.5	.3	.12	
5/23	116-1A	8,700	91	200	205	67	50	1.3	1.1	.13	
5/25	106-1B	8,300	89	580	595	69	100	2.1	1.4	.11	
5/25	118-1A	17,900	87	395	395	66	25	9.8	8.2	.61	
5/25	114-1A	17,600	90	595	585	69	50	10.4	8.1	.59	
5/25	117-1A	13,100	90	595	600	69	75	4.8	3.4	.28	

Table D-2

PRESSURE DROP DATA FROM SODA-ASH RUNS WITH AIR AND SO_2 GAS MIXTURES: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Liquor Flow Rate to Venturi, gpm	Liquor Temperature, °F	Plug Position, % Open	Pressure Drop, in. H_2O			Replicate Runs
							Total	Venturi	Mist Elim.	
7/6-7	202-1A	23,100	93	200	71	59	7.4	4.6	.96	
7/7	202-1B	23,300	97	200	70	↓	7.3	4.5	.99	C
7/9	202-1C	23,300	97	200	73	↓	7.4	4.7	.99	C
7/9	202-1D	23,300	101	190	74	↓	7.3	4.6	.98	
7/9	208-1A	23,400	104	580	76	80	10.0	6.8	.99	D
7/9	20 -1A	11,800	105	565	77	40	5.2	4.5	.22	E
7/10	201-1A	17,500	99	185	77	40	5.9	4.5	.56	
7/10	202-1E	23,400	103	190	76	60	7.2	4.5	.98	
7/10	203-1A	23,500	105	385	78	40	13.5	10.4	.98	
7/10	204-1A	11,600	106	180	79	40	2.5	2.1	.23	
7/10	205-1B	11,600	104	580	79	40	5.3	4.6	.23	E
7/10-11	206-1A	17,400	102	385	79	80	4.7	3.2	.50	
7/11	207-1A	11,500	102	370	79	59	2.9	2.2	.23	
7/11	208-1B	23,500	100	595	79	81	10.5	7.1	1.01	D
7/11	209-1A	17,600	101	595	78	60	7.9	6.1	.54	
7/11	250-1A	23,300	105	395	78	60	9.7	6.9	.98	F
7/11	251-1A	23,400	107	385	78	↓	9.6	6.8	.95	
7/11	253-1A	11,800	107	380	79	↓	2.8	2.3	.23	
7/11	250-1B	23,400	105	355	79	↓	9.4	6.6	.97	F
7/11	254-1A	23,400	103	590	79	60	12.9	9.5	.97	
7/11-12	255-1A	11,500	102	215	79	↓	2.0	1.6	.23	
7/12	254-1B	23,300	100	590	79	↓	13.0	9.6	.98	
7/12	256-1A	11,500	99	580	79	↓	4.0	3.3	.22	
7/12	257-1A	17,400	100	230	78	↓	4.7	3.2	.54	
7/12	258-1A	17,600	99	385	78	↓	6.1	4.6	.51	
7/13	259-1A	23,400	102	280	78	60	8.7	5.8	.92	G
7/13	260-1A	23,400	99	570	76	↓	12.7	9.2	1.00	H
7/13	261-1A	11,600	102	585	78	↓	3.9	3.3	.23	I
7/13	262-1A	11,600	105	305	79	↓	2.4	1.9	.20	J
7/13	259-1B	23,400	108	290	81	↓	8.5	5.9	.98	G
7/13-14	260-1B	23,400	104	590	79	60	12.7	9.4	1.02	H
7/14	261-1B	11,500	101	575	78	↓	3.8	3.2	.22	I
7/14	262-1B	11,500	101	310	78	↓	2.4	1.9	.19	J
7/14-16	259-1C	23,400	105	280	80	↓	8.4	5.7	.99	G
7/16-17	241-1A	11,500	85	390	75	1	7.0	6.4	.22	
7/17-18	243-1A	23,300	105	380	79	67	8.7	6.0	.99	
7/18-19	243-1B	23,300	106	380	80	50	11.0	8.3	.96	K
7/19	244-1A	23,300	108	380	80	50	11.2	8.6	.99	K
7/20	260-1C	23,400	103	385/600[a]	78	46	12.4	9.1	1.04	

(a) 385 gpm to venturi; 600 gpm to spray tower (single header).

Table D-3

PRESSURE DROP DATA FROM SODA-ASH RUNS WITH FLUE GAS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Gas Flow Rate, acfm	Gas Temperature, °F	Liquor Flow Rate, gpm		Liquor Temperature, °F	Plug Position, % Open	Pressure Drop, in. H_2O			Replicate Runs
				Venturi	Spray Tower			Total	Venturi	Mist Elim.	
7/21-22	271-1A	14,800	330	190	0	100	60	2.0	1.5	.20	
7/22	270-1A	30,000	342	395	↓	104	↓	10.3	7.7	1.00	
7/22	273-1A	14,900	331	565	↓	114	↓	4.2	3.6	.19	
7/23	272-1A	30,000	341	570	↓	109	↓	13.7	10.8	.93	
7/23	275-1A	14,900	331	390	↓	107	↓	3.0	2.7	.19	
7/23	274-1A	30,000	345	225	↓	106	↓	8.3	5.7	.90	
7/23	271-1B	15,000	330	200	↓	109	↓	2.0	1.6	.19	
7/23	274-1B	30,000	346	195	↓	110	↓	7.6	5.3	.96	
7/23	270-1B	29,900	347	400	↓	112	↓	10.7	8.0	.92	
7/24	281-1A	29,700	345	380	0	109	52	11.8	9.1	.92	
7/24-25	280-1A	14,800	334	385	↓	107	0	8.2	7.7	.19	
7/26	286-1A	20,100	340	580	↓	99	11	13.4	12.6	.38	L
7/29	287-1A	20,000	326	580	↓	99	17	11.5	10.3	.40	
7/29	288-1A	20,000	329	580	↓	99	29	9.9	8.8	.42	
7/29-30	289-1A	19,700	328	585	↓	100	11	12.0	11.6	.39	M
7/30	291-1A	19,700	307	585	↓	99	10	12.4	11.6	.37	M
7/31-8/1	292-1A	19,900	330	610	↓	102	26	10.8	10.1	.41	
8/1-2	299-1A	30,000	337	280	0	108	59	8.7	6.6	1.01	N
8/4	310-1A	30,000	344	290	0	110	59	9.0	6.9	1.02	N
8/4-5	311-1A	19,900	332	570	↓	98	10	12.6	11.8	.44	L

Table D-4

PRESSURE DROP DATA
FROM AIR/WATER RUNS: TCA SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Water Flow Rate, gpm	Water Temperature, °F	Number of Screens	Spheres[b]	Pressure Drop, in. H_2O			Condition of Run
								Total	Top Stage	Mist Elim.	
[illegible]	101-2C	18,100	83	[illegible]	70	3[a]	yes	[illegible]	1.37	.16	A
[illegible]	102-2C	10,900	86	790	70			2.4	1.76	.04	
[illegible]	103-2A	13,800	88	0	–			1.0	.94	.07	
[illegible]	106-2A	22,600	86	1,180	61			5.2	2.86	.41	
[illegible]	104-2A	17,700	[illegible]	[illegible]	64			2.2	1.50	.15	
[illegible]	105-2A	18,100	[illegible]	[illegible]	66			[illegible]	1.74	[illegible]	A
[illegible]	108-2A	13,400	[illegible]	[illegible]	68			2.8	1.47	.08	[illegible]
[illegible]	110-2A	22,800	[illegible]	808	70			[illegible]	2.26	.27	
[illegible]	109-2A	17,000	91	0				1.2	.94	.14	
[illegible]	112-2A	8,900	84	0				1.0	.90	[illegible]	
[illegible]	107-2A	8,800	90	1,165	68			[illegible]	2.11	[illegible]	
[illegible]	120-2A	23,900	98	0				[illegible]	[illegible]	.24	
[illegible]	111-2A	13,200	94	400	68			[illegible]	1.44	.06	B
[illegible]	113-2A	13,200	[illegible]	805	68			[illegible]	1.52	.08	
[illegible]	114-2A	18,000	104	1,210	70			[illegible]	2.38	.18	
[illegible]	115-2A	23,500	102	410	71			[illegible]	1.4?	.26	
[illegible]	117-2A	9,000	100	415	70			[illegible]	[illegible]	.03	
[illegible]	118-2A	13,400	90	1,215	70			[illegible]	2.2?	.09	
[illegible]	119-2A	16,100	[illegible]	805	68			[illegible]	1.91	.17	A
[illegible]	116-2A	13,200	87	405	70			2.0	1.47	.08	B

(a) Refers to screens, for top bed.
(b) Static height of spheres = 10 inches/bed.

Table D-5

PRESSURE DROP DATA
FROM SODA-ASH RUNS WITH AIR AND SO_2 GAS MIXTURES: TCA SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Liquor Flow Rate, gpm	Liquor Temperature, °F	Number of Screens	Spheres[c]	Pressure Drop, in. H_2O			Replicate Runs
								Total	Bottom Stage	Mist Elim.	
6/21	201-2B	23,000	86	905	71	4[a]	yes	18.4	2.22	.26	
6/23	201-2C	17,400	99	915	70	2[b]	yes	3.5	1.82	.13	
6/28	201-2H	17,700	100	855	77	0	no	1.3	.23	.12	C
6/30	201-2L	17,400	95	920	75	0	no	1.4	.24	.13	C
7/3	225-2C	17,700	98	925	75	0	no	1.4	.26	.12	D
7/3	226-2C	11,900	99	640	74	↓	↓	0.8	.14	.04	
7/3	227-2C	23,600	101	610	76	↓	↓	1.6	.31	.24	
7/3	228-2C	11,700	100	1,180	77	↓	↓	1.5	.22	.05	
7/3	229-2C	23,500	100	1,190	77	↓	↓	2.1	.35	.23	
7/4	230-2C	17,600	100	915	76	↓	↓	1.4	.24	.12	D
7/6-7	231-2A	23,300	95	590	70	2	no	2.0	.39	.28	E
7/7	232-2A	11,800	92	565	70	↓	↓	1.0	.17	.07	
7/7	233-2A	23,300	94	590	68	↓	↓	2.1	.39	.26	E
7/8	234-2A	23,300	94	1,190	72	↓	↓	3.2	.53	.27	F
7/8-9	235-2A	23,300	99	540	72	↓	↓	1.7	.37	.26	
7/9	236-2A	23,400	100	1,165	72	↓	↓	2.6	.60	.28	F
7/11	241-2A	11,800	107	1,180	74	4	yes	5.6	2.20	.06	
7/11-12	245-2A	23,300	101	610	74	↓	↓	8.3	2.03	.27	
7/12-13	248-2A	21,100	80	1,190	73	↓	↓	12.5	2.43	.23	
7/13-14	249-2A	11,800	107	1,190	75	↓	no	1.7	.24	.06	
7/14	250-2A	23,400	103	615	76	↓	no	2.0	.29	.26	
7/15	260-2A	17,800	103	860	79	2	yes	3.2	2.00	.12	
7/15	261-2A	12,000	102	615	79	↓	↓	2.1	1.53	.04	
7/15	262-2A	23,300	101	595	80	↓	↓	3.6	1.82	.21	

(a) Refers to screens for bottom and middle beds.
(b) Refers to screens for bottom bed.
(c) Static height of spheres = 10 inches/bed.

Table D-6

PRESSURE DROP DATA
FROM SODA-ASH RUNS WITH FLUE GAS: TCA SYSTEM

Date	Run No.	Gas Flow Rate, acfm	Gas Temperature, °F	Liquor Flow Rate, gpm	Liquor Temperature, °F	Number of Screens	Spheres[(b)]	Pressure Drop, in. H_2O			Replicate Runs
								Total	Bottom Stage	Mist Elim.	
7/20-22	271-2A	15,000	306	585	102	4[(a)]	yes	5.5	1.59	.06	G
7/24-25	272-2A	15,400	311	580	99	↓	↓	5.6	1.65	.06	G
7/28	273-2A	15,100	299	1,180	103	↓	↓	9.3	2.20	.03	
7/28-29	274-2A	22,430	298	1,190	106	4	yes	6.4	2.10	.10	H
7/29-30	278-2A	22,500	299	600	105	↓	↓	4.4	1.51	.12	
7/30	276-2A	22,500	284	1,182	104	↓	↓	6.4	2.13	.11	H

(a) Refers to screens for bottom and middle beds.
(b) Static height of spheres = 10 inches/bed.

Table D-7

PRESSURE DROP DATA FROM AIR/WATER RUNS: MARBLE-BED SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Water Flow Rate, gpm		Water Temperature, °F	Marble Height, in.	Weir Height, in.	Turbulent Layer Height, in.	Pressure Drop, in. H_2O			Replicate Runs
				Bottom Sprays	Top Sprays					Total	Bed and Turbulent Layer	Mist Eliminator	
3/31	101-3A	9,700	70	0	0	-	3.5	8	-	0.7	0.2	.06	
5/9	101-3B	8,500	71	0	0	-	↓	↓	-	0.6	0.5	.07	
5/10	103-3A	17,700	81	405	150	60			14	7.0	6.3	.28	
5/10	105-3A	17,400	84	280	210	60			N.R.[a]	6.3	5.7	.26	A
5/12	106-3A	9,200	90	155	0	64			0	1.0	0.8	.05	
5/16	107-3A	13,200	85	405	0	64			6	5.7	5.4	.15	
5/16	110-3A	13,200	84	150	0	64			1	2.9	2.6	.15	B
5/16	108-3A	17,500	83	270	0	64			5	6.0	5.6	.28	
5/16	114-3A	23,100	96	400	205	67			19	8.7	6.9	.48	
5/16	109-3B	22,900	83	0	0	-			-	4.0	3.2	.49	
5/16	115-3A	17,700	96	265	200	67			11	6.5	5.9	.27	A
5/17	111-3A	8,400	88	280	200	66			6	4.1	4.0	.08	
5/17	116-3A	8,400	87	405	200	66			7	4.8	4.8	.05	
5/18	119-3A	23,200	87	275	200	66			13	7.5	6.5	.52	
5/18	120-3A	13,200	85	150	0	66			1	2.6	2.3	.15	B
5/18	102-3C	13,300	92	275	0	68			10	5.0	4.7	.14	
5/19	117-3A	13,400	90	150	200	67			7	4.9	4.6	.15	
5/19	112-3B	13,400	90	0	200	67			N.R.	4.9	4.6	.15	
5/19	103-3B	17,700	87	400	0	66			10	6.7	6.2	.29	
5/19	118-3B	17,900	91	0	200	66			9	5.7	5.1	.29	

(a) Not recorded.

Table D-8

PRESSURE DROP DATA FROM SODA-ASH RUNS WITH AIR AND SO_2 GAS MIXTURES: MARBLE-BED SYSTEM

Date	Run No.	Air Flow Rate, acfm	Air Temperature, °F	Liquor Flow Rate, gpm		Liquor Temperature, °F	Marble Height, in.	Weir Height, in.	Turbulent Layer Height, in.	Pressure Drop, in. H_2O			Replicate Runs
				Bottom Sprays	Top Sprays					Total	Bed and Turbulent Layer	Mist Eliminator	
6/29	201-3A	19,400	101	190	195	77	5	8	23	12.3	8.5	.33	
6/30	221-3A	19,400	96	108	0	76	↓	↓	8	8.1	7.3	.36	
6/30	220-3A	19,400	95	108	0	76	↓	↓	N.R.[a]	12.4	8.0	.37	
7/1	212-3A	18,600	99	190	195	77	2	8	7	6.0	4.5	.20	C
7/1	222-3A	23,500	106	208	0	81	↓	↓	19	7.3	6.8	.49	
7/1	223-3A	15,900	108	210	0	82	↓	↓	11	6.8	5.8	.20	
7/1	214-3A	18,700	97	205	190	79	↓	↓	14	7.1	5.8	.20	
7/2	224-3A	23,200	95	210	0	77	↓	↓	12	6.9	4.9	.52	D
7/2	219-3A	23,300	99	210	215	77	↓	↓	17	7.9	6.7	.49	
7/2-3	225-3A	15,700	99	215	0	78	↓	↓	8	4.5	4.1	.22	E
7/3	226-3A	23,200	97	195	0	76	↓	↓	11	5.9	4.9	.53	D
7/3	227-3A	18,600	98	200	0	77	↓	↓	8	4.8	4.2	.21	E
7/19	228-3A	23,400	107	200	0	84	2	8	14	6.3	5.1	.49	D
7/19	229-3A	18,700	106	405	195	84	↓	↓	N.R.	6.4	5.5	.19	
7/20	230-3A	23,400	103	405	185	84	↓	↓	N.R.	7.4	5.8	.49	
7/20	231-3A	23,400	103	205	195	83	↓	↓	N.R.	6.5	5.2	.49	
7/20	232-3A	15,700	101	405	0	83	↓	↓	N.R.	6.1	5.4	.21	
7/20	233-3A	18,900	106	205	0	85	↓	↓	6	5.2	4.5	.19	
7/21	234-3A	18,700	104	205	195	85	↓	↓	8	5.6	4.9	.19	C
7/21	235-3A	23,300	102	400	0	84	↓	↓	11	6.9	5.6	.50	
7/21	250-3A	23,500	104	208	0	85	5	8	7	9.1	8.0	.50	
7/21-2	251-3A	21,400	107	400	0	84	↓	↓	12	10.1	8.8	.50	
7/22	252-3A	23,500	106	200	195	84	↓	↓	12	9.5	8.1	.48	
7/22	253-3A	23,600	108	405	190	84	↓	↓	22	13.7	9.1	.60	
7/23	254-3A	23,300	100	205	0	83	↓	11	12	9.4	8.1	.50	
7/23	255-3A	23,400	107	405	0	85	↓	↓	17	11.1	8.9	.49	
7/23	256-3A	23,400	110	208	190	85	↓	↓	12	10.2	8.6	.47	
7/23	257-3A	23,400	110	400	195	85	↓	↓	22	13.5	9.0	.50	

(a) Not recorded

Table D-9

PRESSURE DROP DATA FROM SODA-ASH RUNS WITH FLUE-GAS: MARBLE-BED SYSTEM

Date	Run No.	Gas Flow Rate, acfm	Gas Temperature, °F	Liquor Flow Rate, gpm		Liquor Temperature, °F	Marble Height in.	Weir Height in.	Turbulent Layer Height in.	Pressure Drop, in. H_2O			Replicate Runs
				Bottom Sprays	Top Sprays					Total	Bed and Turbulent Layer	Mist Eliminator	
7/28-30	2-1-3A	20,000	315	605	0	102	5	11	19	12.6	8.4	.26	F
7/30	2-3-3A	20,100	306	305	↓	100	↓	↓	9	7.4	6.5	.16	G
7/31-8/1	2-4-3A	20,100	323	305	↓	97	↓	↓	N.R.[a]	7.4	6.4	.15	G
8/1	2-2-3A	20,000	309	603	↓	103	↓	↓	N.R.	12.9	8.1	.22	F

(a) Not recorded.

D.2 SULFUR DIOXIDE REMOVAL DATA FROM SODIUM CARBONATE TESTS

A summary of the SO_2 removal data from the sodium carbonate runs is shown in Tables D-10 through D-16. The SO_2 removals have all been corrected for the dilution effect of water vapor and reheater gas pickup by the flue gas.

The observed variations in SO_2 removal for the sodium carbonate runs were as follows:

Inlet Liquor pH	Percent SO_2 Removal	Observed Variation in SO_2 Removal[a]
8.5 - 9.5	85 - 100 50 - 80	±1% ±2%
6.0 - 7.5	90 - 100 50 - 80	±3% ±7%

[a] See replicate runs in Tables D-10 through D-16.

The variations in replicate runs appeared to be a function of pH level* and the magnitude of SO_2 removal. The observed variations were also functions of the scrubber system. For example, Na^+ concentration was easier to control on the venturi system than on the TCA and Marble-Bed systems. Consequently, the variations in SO_2 removal were less for the venturi system than for the other two systems for the gas/liquid-side controlled tests.

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* At high concentration/pH, the interfacial vapor presssue of SO_2 is essentially zero and gas-side resistance controls. At low concentration/ pH, both gas and liquid-side resistances are important. Since the liquid-side resistance is a function of pH (and Na^+ concentration), variations in inlet liquor pH may have caused the observed variations of SO_2 removal.

Table D-10

SODIUM CARBONATE RUNS WITH AIR AND SO_2 GAS MIXTURES: VENTURI/SPRAY TOWER SYSTEM (RUNS 202-1A TO 251-1B)

Date	Run No.	Nominal Run Specifications[(a)]						Average Percent SO_2 Removal	Replicate Runs
		Air Flow Rate, acfm[(c)]	Liquor Flow Rate, gpm	Plug Position, % Open	Gas Inlet SO_2 Concentration, ppm	Scrubber Inlet Liquor			
						pH	Na^+ Conc., wt%		
7/6-7	202-1A	23,100	200	60	1200	9.5	0.5	80	
7/7	202-1B	↓	↓	↓	↓	8.5	0.5	75	
7/9	202-1C	↓	↓	↓	↓	8.5	1.0	80	
7/9	202-1D	↓	↓	↓	↓	9.5	1.0	80	
7/9	208-1A	23,000	600	80	1200	9.5	1.0	90	A
7/9	205-1A	11,550	600	40	↓	↓	↓	82	B
7/10	201-1A	17,320	200	40	↓	↓	↓	79	
7/10	202-1E	23,100	200	60	↓	↓	↓	79	
7/10	203-1A	23,100	400	40	↓	↓	↓	94	
7/10	204-1A	11,550	200	80	↓	↓	↓	66	
7/10	205-1B	11,550	600	40	↓	↓	↓	83	B
7/10-11	206-1A	17,320	400	80	↓	↓	↓	76	
7/11	207-1A	11,550	400	60	↓	↓	↓	73	C
7/11	208-1B	23,100	600	80	↓	↓	↓	92	A
7/11	209-1A	17,320	600	60	↓	↓	↓	87	
7/11	250-1A	23,100	400	60	600	9.5	1.0	90	D
7/11	251-1A	23,100	↓	↓	1200	↓	↓	90	E
7/11	252-1A	11,550	↓	↓	1200	↓	↓	70	C
7/11	253-1A	11,550	↓	↓	600	↓	↓	70	
7/11	250-1B	23,100	↓	↓	600	↓	↓	90	D
7/11	254-1A	23,100	600	60	1200	9.5	1.0	94	
7/11-12	255-1A	11,550	200	↓	↓	↓	↓	64	
7/12	256-1A	11,550	600	↓	↓	↓	↓	80	
7/12	257-1A	17,320	200	↓	↓	↓	↓	75	
7/12	258-1A	17,320	400	↓	↓	↓	↓	82	
7/12	251-1B[(b)]	23,100	400	↓	↓	↓	↓	90	E

(a) See Table D-2 for actual (measured) air and liquor flow rates.

(b) Actual flow rates not available in Table D-2.

(c) At ambient conditions.

Table D-11

SODIUM CARBONATE RUNS WITH AIR AND SO_2 GAS MIXTURES: VENTURI/SPRAY TOWER SYSTEM SCRUBBER (RUNS 259-1A TO 260-1C)

Date	Run No.	Nominal Run Specifications[a]						Average Percent SO_2 Removal	Replicate Runs
		Air Flow Rate, acfm[f]	Liquor Flow Rate, gpm	Plug Position, % Open	Gas Inlet SO_2 Concentration, ppm	Scrubber Inlet Liquor			
						pH	Na^+ Conc., wt %		
7/13	259-1A	23,100	300	60	1200	7.0	0.5	74	F
7/13	260-1A	23,100	600	↓	↓	↓	↓	88	G
7/13	261-1A	11,550	600	↓	↓	↓	↓	73	H
7/13	262-1A	11,550	300	↓	↓	↓	↓	59	I
7/13	259-1B	23,100	300	↓	↓	↓	↓	63	F
7/13-14	260-1B	23,100	600	↓	↓	↓	↓	83	G
7/14	261-1B	11,550	600	↓	↓	↓	↓	72	H
7/14	262-1B	11,550	300	↓	↓	↓	↓	58	I
7/14-16	259-1C	23,100	300	↓	↓	↓	↓	69[b]	F
7/16-17	241-1A	11,550	400	Pressure drop = 6 in. H_2O	1200	7.0	0.125	54	
7/17-18	243-1A	23,100	↓	Pressure drop = 6 in. H_2O	↓	7.0	↓	56	
7/18-19	243-1B	23,100	↓	Pressure drop = 9 in. H_2O	↓	7.0	↓	59[c]	
7/19	244-1A	23,100	↓	Pressure drop = 9 in. H_2O	↓	7.75	↓	68[d]	
7/20	260-1C	23,100	400/600[e]	Pressure drop = 9 in. H_2O	1200	7.0	0.125	93	

(a) See Table D-2 for actual (measured) air and liquor flow rates.
(b) 24 hr. run. Variation of SO_2 removal from 66-76%.
(c) Variation of SO_2 removal from 55-69% over 9 hr. period.
(d) Variation of SO_2 removal from 65-74% over 11 hr. period.
(e) 400 gpm to venturi; 600 gpm to spray tower (single header).
(f) At ambient conditions.

Table D-12

SODIUM CARBONATE RUNS WITH FLUE GAS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Nominal Run Specifications [(a)]							Average Percent SO_2 Removal	Replicate Runs
		Gas Flow Rate, acfm [(c)]	Liquor Flow Rate, acfm	Plug Position, % Open	Venturi Pressure Drop, in. H_2O	Scrubber Inlet Liquor		Stoichiometry, moles Na_2CO_3/mole SO_2 absorbed		
						pH	Na^+ Conc., wt%			
7/22	271-1A	15,000	200	60	-	9.5	1.0	-	62	J
7/22	270-1A	30,000	400	↓	-	↓	↓	-	91	K
7/22	273-1A	15,000	600	↓	-	↓	↓	-	83	
7/23	272-1A	30,000	600	↓	-	↓	↓	-	95	
7/23	275-1A	15,000	400	↓	-	↓	↓	-	74	
7/23	274-1A	30,000	200	↓	-	↓	↓	-	86	L
7/23	271-1B	15,000	200	↓	-	↓	↓	-	64	J
7/23	270-1B	30,000	400	↓	-	↓	↓	-	92	K
7/23	274-1B	30,000	200	↓	-	↓	↓	-	84	L
7/24	281-1A	30,000	400	-	9	6.75	0.125	-	39	
7/24-25	280-1A	15,000	400	-	7	6.75	↓	-	40	
7/25	284-1A	30,000	400/600[(b)]	-	9	6.75	↓	-	78	
7/26	286-1A	20,000	600	-	12	-	↓	1.25	60	
7/29	287-1A	↓	↓	-	12	-	↓	1.45	60	
7/29	288-1A	↓	↓	-	9	-	↓	1.45	61	
7/29-30	289-1A	↓	↓	-	12	-	0.15	1.30	67	
7/30	291-1A	↓	↓	-	12	-	0.15	1.55	65	
7/31	292-1A	↓	↓	-	9	-	0.20	1.40	71	
8/1-2	299-1A	30,000	300	60			0.5	-	61	
8/4	310-1A	30,000	300	60		7.0	0.5	-	60	
8/4-5	311-1A	20,000	600	-	12	-	0.2	1.45	69	

(a) See Table D-3 for actual (measured) gas and liquor flow rates.

(b) 400 gpm to venturi; 600 gpm to spray tower (single header).

(c) Hot, unsaturated.

Table D-13

SODIUM CARBONATE RUNS WITH AIR AND SO_2 GAS MIXTURES: TCA SYSTEM

Date	Run No.	Nominal Run Specifications[a]							Average Percent SO_2 Removal	Replicate Runs
		Air Flow Rate, acfm[f]	Liquor Flow Rate, gpm	Gas Inlet SO_2 Concentration, ppm	Scrubber Inlet Liquor		Number of Screens	Spheres[g]		
					pH	Na^+ Conc., wt. %				
6/21	201-2A[e]	17,320	900	900	9.5	0.5	4[b]	Yes	99^+	
6/21	201-2B	23,100	↓	↓	9.5	↓	4	Yes	99^+	
6/23	201-2C	17,320			9.5		2[c]	Yes	97^+	
6/28	201-2H	17,320			9.5		0	No	93	A
6/30	201-2L	17,320			7.0		0	No	91	
7/3	225-2C	17,320	900	900	9.5	0.5	0	No	93	A
7/3	226-2C	11,550	600	↓	↓	↓	↓	↓	90	
7/3	227-2C	23,100	600						90	
7/3	228-2C	11,550	1200						96	
7/3	229-2C	23,100	1200						93	
7/4	230-2C	17,320	900						93	A
7/6-7	231-2A	23,100	600	900	9.5	0.5	2	No	93	B
7/7	232-2A	11,550	↓	↓	↓	↓	↓	↓	94	
7/7	233-2A	23,100							93	B
7/8	234-2A	23,100	1200	900	7.0	0.5	2	No	91	C
7/8-9	235-2A	↓	600	↓	↓	↓	↓	↓	90	
7/9	236-2A		1200						90	C
7/11	241-2A	11,550	1200	1200	6.75	0.125	4	Yes	98	
7/11-12	245-2A	23,100	600	↓	↓	↓	↓	↓	90	
7/12-13	248-2A	23,100	1200						98^+	
7/13-14	249-2A	11,550	1200					No	97	
7/14	250-2A	23,100	600		7.0			No	72[d]	
7/15	260-2A	17,320	900	1200	9.5	1.0	2	Yes	96	
7/15	261-2A	11,550	600	↓	↓	↓	↓	↓	94	
7/15	262-2A	23,100	600						95	

(a) See Table D-5 for actual (measured) gas and liquor flow rates.
(b) Refers to screens for bottom and middle beds.
(c) Refers to screens for bottom bed.
(d) SO_2 removal increasing monotonically during run. Run terminated before steady-state reached.
(e) Actual flow rates not available in Table D-5.
(f) At ambient conditions.
(g) Static height of spheres = 10 inches/bed.

Table D-14

SODIUM CARBONATE RUNS WITH FLUE GAS: TCA SYSTEM

Date	Run No.	Nominal Run Specifications[a]							Average Percent SO_2 Removal
		Gas Flow Rate, acfm[d]	Liquor Flow Rate, gpm	Scrubber Inlet Liquor		Stoichiometry, moles Na_2CO_3/mole SO_2 absorbed	Number of Screens	Spheres[e]	
				pH	Na^+ Conc., wt%				
7/20	270-2A[c]	30,000	600	6.75	0.125	-	4[b]	Yes	92
7/20-22	271-2A	15,000	600	6.75	↓	-	↓	↓	90
7/24-25	272-2A	15,000	600	7.75		-			96
7/25	273-2A	15,000	1200	6.75		-			97
7/28-29	274-2A	22,500	1200	-	0.125	0.85	4	Yes	88
7/29-30	278-2A	↓	600	-	↓	0.95	↓	↓	77
7/30	276-2A		1200	-		0.90			70

(a) See Table D-6 for actual (measured) gas and liquor flow rates.
(b) Refers to screens for bottom and middle beds.
(c) Actual flow rates not available in Table D-6.
(d) Hot, unsaturated.
(e) Static height of spheres = 10 inches/bed.

Table D-15

SODIUM CARBONATE RUNS WITH AIR AND SO_2 GAS MIXTURES: MARBLE-BED SYSTEM

Date	Run No.	Nominal Run Specifications[(a)]								Turbulent Layer Height, in.	Average Percent SO_2 Removal	Replicate Runs
		Air Flow Rate, acfm[(c)]	Liquor Flow Rate, gpm		Gas Inlet SO_2 Concentration, ppm	Scrubber Inlet Liquor		Marble Height, in.	Weir Height, in.			
			Bottom Sprays	Top Sprays		pH	Na^+ Conc., wt. %					
6/29	201-3A	19,250	400	200	1200	9.5	0.5	5	8	23	99$^+$	
6/30	221-3A	19,250	300	0	↓	↓	↓	↓	↓	8	91	
6/30	220-3A	19,250	600	0							98$^+$	
7/1	212-3A[(b)]	15,400	200	200	1200	9.5	0.5	2	8	7	92	E
7/1	213-3A	23,100	200	200	↓	↓	↓	↓	↓	11	91	C
7/1	222-3A	23,100	600	0						19	94	
7/1	223-3A	15,400	600	0						11	97	
7/1	214-3A	15,400	600	200						14	98$^+$	
7/2	224-3A	23,100	200	0						12	85	A
7/2	215-3A	23,100	600	200						17	96	
7/3	225-3A	15,400	200	0						8	91	B
7/3	226-3A	23,100	200	0						11	81	A
7/3	227-3A	15,400	200	0						8	86	B
7/19	228-3A	23,100	200	0	1200	9.5	1.0	2	8	14	90	A
7/19	229-3A	15,400	400	200	↓	↓	↓	↓	↓		97	
7/20	230-3A	23,100	400	200							95	
7/20	231-3A	23,100	200	200							92	C
7/20	232-3A	15,400	400	0							95	
7/20	233-3A	15,400	200	0						6	93	B
7/21	234-3A	15,400	200	200						8	94	E
7/21	235-3A	23,100	400	0						11	93	
7/21	250-3A	23,100	200	0	1200	9.5	1.0	5	8	7	93	
7/21-22	251-3A	↓	400	0	↓	↓	↓	↓	8	12	96	
7/22	252-3A		200	200					8	12	95	
7/22	253-3A		400	200					8	22	98$^+$	
7/23	254-3A		200	0					11	12	94	
7/23	255-3A		400	0					11	17	96	
7/23	256-3A		200	200					11	12	95	
7/23	257-3A		400	200					11	22	98$^+$	

(a) See Table D-8 for actual (measured) gas and liquor flow rates.
(b) Actual flow rates not available in Table D-8.
(c) At ambient conditions.

Table D-16

SODIUM CARBONATE RUNS WITH FLUE-GAS: MARBLE-BED SYSTEM

Date	Run No.	Nominal Run Specifications[a]								Turbulent Layer Height, in.	Average Percent SO_2 Removal
		Gas Flow Rate, acfm[b]	Liquor Flow Rate, gpm		Scrubber Inlet Liquor		Stoichiometry, moles Na_2CO_3/mole SO_2 absorbed	Marble Height, in.	Weir Height, in.		
			Bottom Sprays	Top Sprays	pH	Na^+ Conc., wt.%					
7/28-30	261-3A	20,000	600	0	-	0.125	1.05	5	11	19	72
7/30	263-3A	↓	300	↓	-	↓	1.50	↓	↓	9	50
7/31	264-3A	↓	300	↓	-	↓	1.75	↓	↓		50
8/1	262-3A	↓	600	↓	-	↓	1.30	↓	↓		67

(a) See Table D-9 for actual (measured) gas and liquor flow rates.
(b) Hot, unsaturated.

Appendix E

TABULAR LISTING OF LIMESTONE FACTORIAL TEST DATA

Table E-1

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 330 °F	Liquor Flow Rate, gpm		L/G[f] gal/mcf	Stoichiometric Ratio[a]	Percent Solids Recirculated	EHT[k] Residence Time, min.	Pressure Drop., in. H_2O		Inlet SO_2 Concentration, ppm	Percent SO_2 Removal	Number of Spray Headers Used[c]
			Venturi	Spray Tower					Venturi	Spray Tower[b]			
9/6-9	401-1A[d]	20,000	520	635	72	1.55-2.15	8-12	65-70	11.0-13.0	1.0-1.7	2300-3300	81 ±6	4
9/9-10	401-1B[d]	20,000	565	0	36	3.40-4.75	8-10	↓	11.0-13.0	0.2-0.6	2800-3300	37 ±6	(g)
9/21-25	402-1A	20,000	560	600	72	1.50-1.70	7-9	↓	11.5-12.5	1.0-1.7	2200-2700	88 ±3	4
9/25-26	402-1B	19,800	560	0	36	2.15-2.50	7-9	↓	11.5-12.5	0.2-0.6	2400-2800	60 ±5	(g)
10/2-3	403-1A	30,000	560	↓	23	3.15-3.80	7-9	↓	8.8- 9.2	0.8-1.2	2600-2800	41 ±6	↓
10/3-4	404-1A	29,900	280	↓	11	4.70-5.30	5-7	↓	8.8- 9.8	0.8-1.2	2400-2800	35 ±6	↓
10/4-5	405-1A	29,900	270	↓	11	2.90-4.00	5-7	↓	8.5- 9.5	0.8-1.2	2500-2900	36 ±6	↓
10/6-7	406-1A	30,000	550	↓	22	2.85-3.25	4-6	↓	8.5- 9.5	0.8-1.2	2600-3000	49 ±6	↓
10/7-9	407-1A	29,900	545	↓	22	2.65-3.00	6-8	↓	8.5- 9.5	0.8-1.2	2500-3000	47 ±6	↓
10/10-12	408-1A	30,000	540	↓	22	3.35-3.75	6-8	↓	9.0- 9.4	0.8-1.2	2500-3000	51 ±6	↓
10/13-16	409-1A	30,000	250	↓	11	3.05-3.50	5-7	↓	8.2- 9.8	0.8-1.2	2600-3100	46 ±5	↓
10/17-20	410-1A	29,900	560	↓	23	2.75-2.90	5-7	↓	8.5- 9.5	0.8-1.2	2700-3100	55 ±4	↓
10/20-22	411-1A	30,000	555	↓	23	2.65-3.10	6-8	↓	11.5-12.5	0.8-1.2	2800-3200	53 ±5	↓
10/22-23	412-1A	29,900	545	↓	22	2.05-2.60	6-7	↓	11.5-12.5	0.8-1.2	2800-3200	54 ±4	↓
10/23	412-1B	29,900	545	↓	22	1.75-2.35	5-7	↓	8.5- 9.5	0.8-1.2	2900-3100	49 ±4	↓
10/23-24	413-1A	30,000	555	↓	23	3.60-3.80	6-8	↓	8.5- 9.5	0.8-1.2	2900-3100	46 ±3	↓
10/25	414-1B	29,900	280	↓	11	4.40-4.70	6-8	↓	8.5-10.5	0.8-1.2	3000-3200	33 ±2	↓
10/25-30	414-1A	30,000	275	↓	11	4.40-5.30	5-7	↓	11.5-12.5	0.8-1.2	2700-3200	34 ±5	↓
11/8-12	415-1A	30,000	305	↓	13	4.80-5.60	5-7	↓	8.5- 9.5	0.8-1.2	2300-2900	24 ±13[f]	↓
11/12-15	414-1D	29,900	305	↓	13	4.25-4.85	5-7	↓	11.5-12.5	0.8-1.2	2200-3000	33 ±5[f]	↓
11/15-16	414-1C	29,900	305	↓	13	4.80-5.90	5-7	↓	6.0- 6.8	0.8-1.2	2400-3000	28 ±5[f]	↓
12/21-22	417-1A	30,000	605	↓	25	(e)	6-8	↓	9.0-10.0	0.8-1.2	2300-2500	39 ±3	↓
12/23	417-1B	30,000	600	↓	25	↓	6-8	↓	6.0- 6.4	0.8-1.2	2300-2500	35 ±2	↓
12/23-24	419-1A	15,000	605	↓	50	↓	5-7	↓	9.0- 9.4	0.1-0.3	2400-2600	44 ±2	↓
12/24-25	421-1A	15,000	610	↓	50	↓	5-7	↓	8.9- 9.5	0.1-0.3	2200-2800	39 ±2	↓
12/25-26	414-1E	30,000	300	↓	12	↓	5-7	↓	11.5-12.5	0.8-1.2	2200-2800	28 ±2	↓
12/26	414-1H	30,000	300	↓	12	↓	5-7	↓	8.5- 9.5	0.8-1.2	2700-2800	29 ±2	↓
12/26	414-1F	29,900	305	↓	13	↓	5-7	↓	5.7- 6.3	0.8-1.2	2700-2900	26 ±2	↓
12/26	418-1A	15,000	300	↓	25	↓	5-7	↓	7.7- 8.1	0.1-0.3	2700-2900	31 ±2	↓
12/26	418-1B	14,800	600	↓	50	↓	5-7	33	12.0-12.6	0.1-0.3	2700-2900	44 ±2	↓
12/27-28	418-1C	14,900	600	↓	50	↓	5-7	65-70	12.0-13.0	0.1-0.3	2300-2500	44 ±2	↓

NOTE: Footnote definitions are on the following page.

(continued)

Table E-1 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 330 °F	Liquid Flow Rate, gpm		L/G,[j] gal/mcf	Stoichiometric Ratio[a]	Percent Solids Recirculated	EHT Residence Time, min.	Pressure Drop., in. H_2O		Inlet SO_2 Concentration, ppm	Percent SO_2 Removal	Number of Spray Headers Used[c]
			Venturi	Spray Tower					Venturi	Spray Tower[b]			
12/31-1/2	453-1B	14,900	0[h]	460	38	(e)	5-7	40	2.2-2.8	0.1-0.4	2700-3100	53±3	4
1/2-3	453-1C	14,900	↓	450	37	↓	5-7	↓	0.6-0.9	0.1-0.4	2800-3000	50±2	↓
1/3-4	454-1B	14,900		450	37		5-7		0.6-0.9	0.1-0.4	2800-3200	52±3	
1/4-6	456-1A	14,900		450	57		5-7		0.6-0.9	0.1-0.4	3000-3400	48±3	
1/6	458-1A	10,000		455	57		5-7		0.4-0.6	0.1-0.2	3100-3300	66±3	
1/6-7	459-1A	14,900		300	25		5-7	65-70	0.6-0.9	0.1-0.4	3000-3200	39±2	
1/7-8	461-1A	10,000		460	56		5-7	↓	0.4-0.6	0.1-0.2	3100-3300	70±2	
1/8-9	462-1A	29,900		450	19		5-7		1.4-1.6	1.0-1.7	3200-3400	40±2	
1/9	460-1A	29,900		295	12		7-9		1.3-1.7	1.4-1.6	3000-3400	28±2	
1/12-13	460-1B	12,000		320	34		2-3		0.5-0.7	0.1-0.3	2800-3200	46±3	
1/14-15	460-1C	11,600		390	42		3-4		0.6-0.9	0.1-0.2	2800-3200	63±3	
1/23-26	463-1A[i]	20,000		450	28		6-9	56	0.7-1.5	0.1-0.5	2800-3200	42±2	
1/26-27	465-1A	29,900		455	19		7-9	70	1.4-1.5	1.3-1.7	2500-2900	32±2	
1/27	466-1A	30,000		300	12		7-9	106	1.4-1.5	1.2-1.6	3000-3100	26±2	
1/27-28	467-1A	20,200		295	18		7-8	106	0.9-1.2	0.1-0.3	2800-2900	30±2	
1/28	468-1A	19,400		300	20		6-8	106	0.9-1.1	0.1-0.5	2900-3000	33±2	
1/28-29	469-1A	19,400		250	16		6-7	127	0.5-0.9	0.3-0.7	2800-3200	35±2	3(2, 3, 4)
1/29-30	470-1A	20,200		300	19		7-8	106	0.6-0.8	0.4-0.9	2900-3100	39±2	2(2, 4)
1/30	471-1A	20,000		310	20		6-8	106	0.6-0.8	0.7-0.9	3100-3200	39±2	2(1, 4)

Limestone: Fine ground (87% through 200 mesh), except where noted.

(a) Defined as moles $CaCO_3$ added/moles SO_2 absorbed.

(b) Total pressure drop across tower, excluding mist eliminator.

(c) Numbers in parentheses refer to header positions, counting from bottommost header.

(d) Limestone coarse ground (69% through 200 mesh).

(e) Stoichiometries for this period of time are all in excess of 2.0 moles $CaCO_3$/mole SO_2 inlet.

(f) SO_2 removals for these runs are doubtful due to problems with the DuPont analyzers and wet SO_2 analyzers. The values given are based on the wet analyses.

(g) Spray tower not in use.

(h) Approximately 12 gpm of water was used for cooling purposes.

(i) Data point from limestone depletion run at high stoichiometry.

(j) At scrubber outlet conditions.

(k) Effluent hold tank.

Table E-1 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Gas Temperature, °F				Liquor Temperature, °F				Ambient Temp., °F	Liquor pH[h]						
		Hot Gas	Venturi Inlet	Spray Tower	Tower Outlet	Venturi Inlet	Venturi Outlet	EHI[i] Outlet	Spray Tower Outlet		Venturi Inlet	Venturi Outlet	EHI[i] Outlet[a]	Spray Outlet	Recirc. Tank Outlet	Clarifier Underflow	Pond Return
9/6-9	401-1A	320-340	305-325	117-123	124-130	115-121	118-128	-	118-124	65-84	6.2-6.9	6.0-6.5	6.1-6.9	6.0-6.8	-	6.1-6.8	
9/9-10	401-1B	320-340	305-325	115-120	122-128	115-117	115-122	115-118	(d)	60-80	6.2-6.4	6.1-6.2	6.2-6.4	(d)	(d)	6.4-6.7	
9/21-25	402-1A	320-345	300-325	115-125	120-130	114-122	117-126	-	116-125	61-80	6.1-6.4	5.8-6.2	6.1-6.4	5.9-6.2	-	6.4-7.0	
9/25-26	402-1B	325-350	310-325	121-124	129-134	118-120	123-126	120-123	(d)	70-80	6.1-6.4	5.8-6.0	6.0-6.4	(d)	(d)	6.4-7.0	
10/2-3	403-1A	325-345	310-325	116-124	(c)	114-117	120-123	114-120	↓	54-74	6.2-6.4	(e)	6.1-6.2	↓	↓	6.6-6.7	
10/3-4	404-1A	345-350	325-330	119-122	↓	110-112	122-124	113-115	↓	65-67	6.2-6.4	↓	6.2-6.5	↓	↓	-	
10/4-5	405-1A	330-350	320-330	119-125	↓	110-114	117-125	115-117	↓	57-78	6.4-6.5	↓	6.1-6.2	↓	↓	6.6-6.7	
10/6-7	406-1A	330-350	320-330	117-120	↓	114-118	121-125	116-121	↓	54-79	6.3-6.4	↓	6.1-6.2	↓	↓	6.5	6.0-6.1
10/7-9	407-1A	330-345	318-327	117-122	↓	113-117	120-127	116-119	↓	45-75	6.1-6.3	↓	6.1-6.2	↓	↓	6.4	6.0-6.1
10/10-12	408-1A	337-350	317-327	117-123	↓	113-119	120-126	116-121	↓	50-75	5.9-6.4	↓	6.1-6.3	↓	↓	6.0-6.8	6.1-6.4
10/13-16	409-1A	330-340	320-330	118-125	↓	111-115	121-124	115-119	↓	58-65	6.0-6.3	↓	6.0-6.1	↓	↓	6.2-6.5	6.1-6.3
10/17-20	410-1A	320-330	308-325	112-121	↓	97-114	116-125	107-116	↓	38-50	6.2-6.8	↓	6.0-6.1	↓	↓	6.6-6.9	7.5-7.6
10/20-22	411-1A	320-340	310-325	116-121	↓	107-114	120-123	115-117	↓	40-56	6.2-6.4	↓	6.0-6.2	↓	↓	6.6-6.8	7.3-7.5
10/22-23	412-1A	330-345	315-325	118-121	↓	114-116	121-126	117-119	↓	61-70	6.2-6.3	↓	6.0-6.1	↓	↓	6.7-6.8	7.3-7.4
10/23	412-1B	325-335	315-325	116-121	↓	114-115	122-124	117-118	↓	60-70	6.1-6.2	↓	6.0-6.1	↓	↓	6.8	7.4
10/23-24	413-1A	321-335	309-322	114-121	↓	108-115	120-126	111-118	↓	47-54	6.1-6.3	↓	5.9-6.0	↓	↓	6.8-7.1	7.4
10/25	414-1B	325-333	312-319	106-124	↓	106-109	120-128	111-112	↓	46-48	6.5	↓	5.9-6.0	↓	↓	6.6	7.2
10/25-30	414-1A	325-340	310-325	116-122	↓	106-109	120-125	112-114	↓	46-60	6.1-6.3	↓	5.9-6.1	↓	↓	6.4-6.8	7.1-7.8
11/8-12	415-1A	320-345	305-330	115-124	↓	108-113	120-129	113-117	↓	48-58	6.0-6.3	↓	5.8-6.0	↓	↓	6.3-6.5	6.4-7.1
11/12-15	414-1D	305-330	300-315	116-124	↓	108-113	120-12	112-118	↓	46-62	5.9-6.2	↓	5.8-5.9	↓	↓	6.0-6.5	
11/15-16	414-1C	315-323	304-311	108-120	↓	88-103	117-126	104-113	↓	35-39	6.0-6.3	↓	5.9-6.0	↓	↓	6.0-6.1	
12/21-22	417-1A[f]	315-330	300-315	85-107	104-120	70-96	111-122	107-114	↓	33-36	6.2-6.4	↓	6.1	↓	↓	6.8	
12/23	417-1B[f]	305-317	295-308	94-113		76-91	107-121	110-113	↓	32-35	6.1-6.4	↓	6.2	↓	↓	-	
12/23-24	419-1A	305-325	295-315	102-113	110-123	87-100	114-120	100-113	↓	32-42	6.1-6.4	↓	6.3-6.5	↓	↓	-	
12/24-25	421-1A[f],[g]								↓		6.1-6.4	↓	6.0-6.1	↓	↓	6.5-6.6	
12/25-26	414-1E[f],[g]								↓		6.1-6.3	↓	6.1-6.2	↓	↓	-	
12/26	414-1G[f]	319-322	310-312	100-101	119-121	84-86	111-112	112-113	↓	32-33	6.3-6.4	↓	6.1-6.2	↓	↓	-	
12/26	414-1F[f]	315-325	302-312	103-106	122-129	81-92	114-117	112-114	↓	30-34	6.3-6.4	↓	6.1-6.2	↓	↓	-	
12/26	418-1A[f],[g]								↓		6.2-6.4	↓	5.9-6.2	↓	↓	-	
12/26	418-1B[f],[g]								↓		6.1-6.3	↓	6.1-6.2	↓	↓	-	
12/27-28	418-1C[f]	290-325	275-315	90-106	110-128	75-109	108-116	102-110	↓	29-49	6.0-6.4	↓	6.2-6.6	↓	↓	-	

NOTE: Footnote definitions are on the following page.

Table E-1 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: VENTURI/SPRAY TOWER SYSTEM

Date	Run No.	Gas Temperature, °F				Liquor Temperature, °F				Ambient Temp., °F	Liquor pH [b]						
		Hot Gas	Venturi Inlet	Spray Tower	Tower Outlet	Venturi Inlet	Venturi Outlet	EHT[i] Outlet	Spray Tower Outlet		Venturi Inlet	Venturi Outlet	EHT[i] Outlet[f]	Spray Outlet	Recirc. Tank Outlet	Clarifier Underflow	Pond Return
12/31-1/2	453-1B	295-318	102-120	101-133	107-113	(h)	118-125	103-108	98-111	30-43	(h)	(h)	6.6	—	6.1	7.5	7.5
1/2-3	453-1C	305-320	108-120	127-163	109-118		119-128	105-109	109-114	35-52			6.3	—	5.6-5.8	6.4	7.45
1/3-4	454-1B	307-322	110-115	125-144	105-114		120-129	103-109	102-114	40-45			6.4	—	—	6.4	7.2
1/4-6	456-1A	293-320	108-120	100-134	107-114		91-122	89-110	79-116	22-43			6.2	—	5.7	6.0	7.2
1/6	458-1A	270-301	103-113	114-138	92-102		90-105	90-96	78-87	23-28			6.7	—	6.3	6.3	7.0
1/6-7	459-1A	298-310	107-120	100-148	104-112		100-121	88-96	80-96	26-29			6.8	—	6.2	6.6	7.1
1/7-8	461-1A	296-301	106-118	113-146	90-100		104-118	88-95	78-92	26-29			6.65	—	6.1-6.25	6.6	7.3
1/8-9	462-1A	310-320	112-121	92-107	105-117		110-120	88-107	88-100	22-28			6.2	—	5.75	—	—
1/9	460-1A	305-322	111-123	79-97	113-119		98-114	93-104	80-101	17-26			6.5	—	5.8	6.4	7.2
1/12-13	460-1B	298-309	101-116	132-170	96-109		104-126	86-99	71-103	24-41			6.2-6.3	—	5.9	6.4-6.5	7.0-7.2
1/14-15	460-1C	298-319	105-115	128-147	100-108		106-123	92-101	76-104	30-46			6.9	—	6.3	6.6	7.2
1/23-26	463-1A	300-318	110-118	107-124	112-115		117-125	106-108	97-113	34-49			6.3	—	—	—	—
1/26-27	465-1A	306-328	107-121	117-127	112-121		123-131	107-110	113-120	44-45			6.6	—	—	—	—
1/27	466-1A	317-328	111-120	118-127	119-126		124-131	108-111	116-123	44-48			6.6	6.3	—	6.4	—
1/27-28	467-1A	304-324	107-118	117-127	117-124		120-131	106-111	111-118	44-48			6.6	—	—	—	—
1/28	468-1A	295-319	108-120	105-128	110-121		114-132	102-109	94-119	32-44			6.6	—	6.0	6.4	—
1/28-29	469-1A	307-326	110-122	97-138	111-119		107-126	100-102	86-106	26-33			6.5	—	5.9	6.3	—
1/29-30	470-1A	306-318	112-120	99-112	111-117		109-120	102-103	87-95	25-30			6.4	—	—	—	—
1/30	471-1A	308-316	110-116	108-118	112-113		113-123	102-103	91-102	25-38			6.4	—	—	—	—

(a) EHT outlet equals spray tower inlet when spray tower is in use.

(b) Single values indicate only one pH reading taken.

(c) Digital output in error.

(d) Spray tower not in use.

(e) Unable to sample.

(f) pH's taken from in-line meters. Laboratory pH not taken.

(g) Magnetic tape records not available.

(h) Venturi not in use.

(i) Effluent hold tank.

Table E-2

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: TCA SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 310 °F	Liquor Flow Rate, gpm	L/G$^{(g)}$ gal/mcf	Stoichio-metric Ratio$^{(a)}$	Percent Solids Recirc.	Effluent Tank Residence Time, min.	Ht. of Spheres per bed, in.	No. of Grids	Pressure Drop,$^{(c)}$ in. H_2O	Inlet SO_2 Conc., ppm	Percent Removal, SO_2
10/9-17	401-2A	20,000	1180	74	1.54-1.96	7.2-8.4	4.6	10	6	8.2-9.8	2600-3300	92 ±3
10/17-20	402-2A	15,000	585	49	2.09-2.44	7.5-9.3	9.2	↓	↓	4.3-5.5	2850-3250	89 ±3
10/20-21	404-2A	20,000	1220	76	1.56-1.72	8.4-9.2	4.6	↓	↓	9.1-9.9	2650-2950	93 ±3
10/21-22	405-2A	15,100	1180	97	1.26-1.62	6.9-8.8	↓	↓	↓	7.1-7.9	2800-3150	94 ±3
10/23-24	408-2A	15,100	1180	97	1.51-1.88	7.0-8.8	↓	↓	↓	7.2-7.6	2950-3200	93 ±3
10/25-26	409-2A	20,100	1180	73	1.65-1.80	7.8-10.7	↓	5	↓	5.9-6.8	2800-3150	89 ±3
10/27-28	410-2A	15,000	1180	98	1.94-2.32	6.8-8.4	↓	↓	↓	4.5-5.1	2550-2950	87 ±4
10/28-29	411-2A	15,100	1180	97	1.41-1.45	6.9-8.4	↓	↓	↓	4.4-5.0	2500-3150	86 ±3
10/29-31	412-2A	27,500	1170	53	1.27-1.34	6.6-9.5	↓	↓	↓	13-15	2850-3150	96 ±3
10/31-11/1	413-2A	27,400	1220	55	1.72-1.86	8.4-9.2	↓	↓	↓	12-15	2400-2900	96 ±3
11/1-3	414-2A	20,100	1200	75	1.56-1.81	7.1-9.2	↓	↓	↓	6.1-7.7	2800-3250	90 ±3
11/25-12/6	WC-2A	20,000	800	50	(e)	12.5-15.5	6.8	0	5	1.4-1.9	2300-3300	62 ±6
12/20-21	WC-4	19,500	1030	65	↓	13.1-15.8	5.3	↓	↓	1.9-2.1	1850-2600	78 ±4
12/21	WC-5	19,200	730	48	↓	13.5-14.0	7.5	↓	↓	1.4-1.6	2450-2600	66 ±2
12/21	WC-6	19,450	515	33	↓	14.2-14.4	9.5	↓	↓	1.2-1.3	2300-2450	60 ±2
12/22	WC-7	19,300	370	24	↓	14.2-14.4	13.2	↓	↓	1.0-1.1	2200-2400	52 ±3
12/22	WC-8	30,050	570	23	↓	14.2-14.4	8.5	↓	↓	2.1-2.4	2400-2450	63 ±1
12/22	WC-9	30,050	815	34	↓	14.2-14.4	6.0	↓	↓	2.5-3.1	2400-2450	72 ±1
12/22-1/9	WC-5A	19,300	730	47	↓	12.7-15.3	7.5	↓	↓	1.3-3.0$^{(d)}$	2150-3350	72 ±7$^{(d)}$
1/9-10	WC-4A	19,100	1070	70	↓	(b)	5.1	↓	↓	3.7-4.0	3200-3250	87 ±1
1/10	WC-6A	19,100	510	34	↓	↓	10.7	↓	↓	2.7-3.1	3100-3200	73 ±2
1/10	WC-7A	19,200	375	24	↓	↓	14.6	↓	↓	2.6-2.8	3050-3150	69 ±1
1/10-11	WC-8A	25,150	460	23	↓	↓	11.4	↓	↓	5.5-5.8	2800-3050	77 ±2
1/11	WC-9A	25,100	680	34	↓	↓	8.1	↓	↓	5.7-6.6	2950-3050	85 ±1
1/11	WC-10	25,000	990	49	↓	↓	5.6	↓	↓	6.4-6.8	2800-2950	90 ±1
1/11-12	WC-11	19,400	745	48	↓	↓	7.5	↓	↓	4.1-4.7	2850-3100	85 ±1
1/12-15	WC-12	19,300	375	24	↓	13.3-14.9	14.6	↓	↓	3.8-4.5	2750-3150	71 ±4

NOTE: Footnote definitions are on the following page.

(Continued)

Table E-2 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: TCA SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 310 °F	Liquor Flow Rate, gpm	L/G,[g] gal/mcf	Stoichio-metric Ratio[a]	Percent Solids Recirc.	Effluent Tank Residence Time, min.	Ht. of Spheres per Bed, in.	No. of Grids	Pressure Drop,[c] in. H_2O	Inlet SO_2 Conc., ppm	Percent Removal, SO_2
1/24-25	415-2A	15,250	1200	98	(e)	7.4-11.3	4.6	5	6	5.0-6.0	2250-2750	95±2
1/25	416-2A	20,000	1195	75	↓	8.1-8.8	↓	5	↓	5.8-6.6	1750-2200	95±1
1/26	417-2A	25,200	1190	59	↓	8.1-8.7	↓	5	↓	9.4-9.7	1700-1850	96±1
1/26	418-2A	15,000	1200	100	↓	8.2-8.7	↓	0	↓	1.9-2.0	2350-2600	84±1
1/26	419-2A	19,300	1210	79	↓	9.2-9.3	↓	0	↓	2.4-2.6	2500-2900	82±1
1/27	420-2A	24,650	1200	61	↓	9.2-10.9	↓	0	↓	3.5-3.7	2850-2950	80±2
1/27-28	421-2A	20,050	1200	75	↓	8.3-9.0	4.6	5	4	6.3-7.0	2600-2850	93±2
1/28	422-2A	20,100	1200	75	↓	8.7-9.4	4.6	↓	↓	6.2-7.0	2550-2800	93±2
1/28-29	426-2A	20,050	1200	75	↓	8.2-10.2	3.8	↓	↓	6.2-6.9	2700-2850	93±2
1/29	423-2A	20,200	1200	74	↓	10.8-15.4	4.6	↓	↓	5.9-6.8	2750-3350	95±2
1/29-30	424-2A	20,000	1200	75	↓	14.0-15.0	4.6	↓	↓	6.4-7.0	2900-3550	96±1
1/31-2/1	427-2A[f]	20,000	1200	75	↓	6.1-7.4	18	↓	↓	5.8-6.0	2200-2500	92±5
2/1	428-2A	15,000	605	50	↓	6.1-6.7	35	↓	↓	2.8-3.2	2300-2450	69±2
2/1	429-2A	24,900	1200	60	↓	6.7-7.0	18	↓	↓	7.0-7.1	2250-2450	94±2
2/1	430-2A	25,000	600	30	↓	7.0-7.9	35	↓	↓	4.3-4.4	2050-2300	69±3
2/1	431-2A	20,000	1200	75	↓	7.9-8.7	18	↓	↓	5.3-5.8	1950-2100	94±1
2/1	432-2A	20,000	600	37	↓	8.7-9.3	35	↓	↓	3.4-3.6	2000-2050	71±1
2/1-2	433-2A	15,050	910	76	↓	9.3-10.1	23	↓	↓	3.6-3.7	1800-1900	91±1
2/2	434-2A	20,000	905	56	↓	9.8-10.1	23	↓	↓	3.7-3.8	1800-2450	89±2
2/2	435-2A	25,000	905	45	↓	9.8-11.2	23	↓	↓	5.5-5.7	2450-2500	88±1

Scrubber Internals: 3 beds when spheres were used.

Limestone: Fine-ground (87% through 200 mesh).

(a) Defined as moles $CaCO_3$ added/mole SO_2 absorbed.

(b) Nominal percent solids was 14% for these runs. Density meter readings were 10-12%. Three laboratory samples taken at 1600 hours on 1/9, 1/11 and 1/12 gave 13.9, 7.7, and 20.2%, respectively.

(c) Pressure drop across the scrubber, excluding mist eliminator and Koch tray (when used).

(d) SO_2 removal increased steadily from 64-67% to 75-79%, pressure drop increased from 1.3-1.6 to 2.6-3.0 in. H_2O, during the 19-day run.

(e) Stoichiometries for this period of time are all in excess of 1.5 moles $CaCO_3$/mole SO_2 absorbed.

(f) Limestone was not added to the system during the run. SO_2 removal dropped steadily from 97 to 86%, and scrubber inlet liquor pH dropped steadily from 6.2 to 5. during the entire run.

(g) At scrubber outlet conditions.

Table E-2 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: TCA SYSTEM

Date	Run No.	Gas Temperature, °F			Bed Temp., °F	Liquor Temp., °F		Ambient Temp., °F	Liquor pH		
		Hot Gas	Scrubber Inlet	Scrubber Outlet		Scrubber Inlet	Scrubber Outlet		Scrubber Inlet	Scrubber Outlet	Clarifier Underflow
10/9-17	401-2A	291-311	124-158	114-130	112-122	109-121	113-125	57-77	5.8-6.1	(a)	6.1-6.6
10/17-20	402-2A	278-295	121-131	102-119	109-117	99-112	107-118	38-50	5.8-6.0	↓	6.5-6.6
10/20-21	404-2A	282-301	124-132	117-123	112-119	111-119	112-122	47-57	5.7-5.9	↓	6.5-7.0
10/21-22	405-2A	288-309	125-135	117-122	112-120	112-120	114-122	57-70	5.6-5.9	↓	6.9-7.0
10/23-24	408-2A	287-294	124-127	(c)	110-114	110-114	112-116	47-65	5.6-5.9	↓	6.7-7.1
10/25-26	409-2A	283-292	270-287	↓	104-115	110-116	112-118	38-59	5.7-6.0	↓	7.1-7.2
10/27-28	410-2A	281-302	275-288	↓	111-119	108-116	111-120	51-60	6.6-6.9	↓	6.5-7.1
10/28-29	411-2A	283-298	256-290	↓	110-114	110-114	112-119	54-59	5.6-5.9	↓	6.3-6.5
10/29-31	412-2A	285-299	285-294	↓	113-122	113-118	115-124	53-62	5.5-5.9	↓	6.4-6.6
10/31-11/1	413-2A	290-315	260-296	↓	116-124	115-122	118-125	65-80	5.8-5.9	↓	6.6-6.8
11/1-3	414-2A	281-301	267-286	↓	112-120	112-121	115-122	45-61	5.7-6.0	↓	6.9-7.2
11/25-12/6	WC-2A	270-302	162-252	↓	110-119	104-117	109-121	37-65	5.9-6.6	5.5-6.7	(b)
12/20-21	WC-4	264-293	118-156	↓	94-117	94-116	106-118	36-48	5.7-6.4	6.3	↓
12/21	WC-5	273-283	122-129	↓	110-115	98-103	110-116	37-40	6.1-6.2	(a)	↓
12/21	WC-6	271-283	121-128	↓	111-114	86-94	110-116	34-36	5.9-6.0	↓	↓
12/22	WC-7	272-289	121-129	↓	110-116	83-90	109-116	33-35	5.9-6.0	↓	↓
12/22	WC-8	287-292	123-131	↓	113-118	91-98	112-119	35-36	5.8-6.0	↓	↓
12/22	WC-9	282-289	121-140	↓	110-114	93-105	108-116	35-37	5.8-5.9	↓	↓
12/22-1/9	WC-5A	265-301	105-134	↓	84-120	69-115	95-119	20-55	6.0-6.6	↓	↓
1/9-10	WC-4A	269-282	119-123	↓	72- 97	64-80	87-103	16-24	6.4	↓	↓
1/10	WC-6A	266-274	116-123	↓	70- 79	58-67	84- 94	14-16	-	↓	↓
1/10	WC-7A	271-276	118-124	↓	80- 94	68-79	93-101	16-25	-	↓	↓
1/10-11	WC-8A	274-286	116-124	↓	84-104	66-87	92-109	18-26	-	↓	↓
1/11	WC-9A	274-278	117-125	↓	82- 91	71-78	93-100	18-26	-	↓	↓
1/11	WC-10	276-283	114-129	↓	86-113	77-88	99-113	27-30	-	↓	↓
1/11-12	WC-11	267-277	116-126	↓	82-114	69-99	92-114	16-36	6.2	↓	↓
1/12-15	WC-12	273-307	116-127	↓	100-119	88-109	102-114	21-46	6.1-6.4	↓	↓

Note: Footnote definitions are on following page.

(Continued)

Table E-2 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: TCA SYSTEM

Date	Run No.	Gas Temperature, °F			Bed Temp., °F	Liquor Temp., °F		Ambient Temp., °F	Liquor pH		
		Hot Gas	Scrubber Inlet	Scrubber Outlet		Scrubber Inlet	Scrubber Outlet		Scrubber Inlet	Scrubber Outlet	Clarifier Underflow
1/24-25	415-2A	252-294	107-131	(c)	93-116	90-116	102-118	33-62	6.0-6.2	–	–
1/25	416-2A	273-292	119-130		109-116	107-113	111-118	45-52	6.1	–	–
1/26	417-2A	276-306	121-129		110-117	101-114	113-119	45-48	6.0-6.1	6.0	7.9
1/26	418-2A	274-282	120-130		110-120	108-117	110-118	44-46	5.9-6.3	–	–
1/26	419-2A	280-301	120-129		112-121	108-115	110-118	45	6.1-6.3	–	–
1/27	420-2A	280-293	122-130		113-121	108-117	114-120	44-45	6.0	5.9	6.8
1/27-28	421-2A	284-302	122-129		111-118	111-117	114-119	44-48	6.2	6.0	–
1/28	422-2A	265-288	117-135		110-124	91-113	112-125	32-45	6.3	6.2	7.5
1/28-29	426-2A	274-280	119-128		95-114	78-92	101-110	26-32	5.8	–	–
1/29	423-2A	275-285	121-130		97-117	84-102	103-120	26-33	6.2	6.2	7.2
1/29-30	424-2A	276-283	121-130		107-118	98-107	111-121	25-30	6.1	6.1	7.1
1/31-2/1	427-2A(d)								5.9-6.2	5.8-6.2	–
2/1	428-2A	256-262	118-120		111-113	109-11	112-114	47-57	6.1-6.3	5.9-6.0	–
2/1	429-2A	276-292	120-127		112-117	112-115	114-118	58-64	6.2	6.0	–
2/1	430-2A	285-295	122-254		116-124	115-117	117-123	65-66	6.2	5.9	–
2/1	431-2A	265-289	120-274		112-115	112-116	113-116	60-66	6.1-6.2	5.8-5.9	–
2/1	432-2A	284-299	122-285		112-118	111-115	112-118	51-60	5.9-6.1	5.8-5.9	–
2/1-2	433-2A	278-286	220-269		109-112	109-111	111-112	48-50	5.9-6.0	5.8-6.0	–
2/2	434-2A	277-289	252-271		110-118	108-115	111-119	46-48	6.0-6.2	6.0	–
2/2	435-2A	278-284	232-255		115-118	114-116	118-120	(d)	6.1-6.2	6.0-6.1	–

(a) Unable to sample.

(b) Laboratory pH not available.

(c) Digital output in error.

(d) No magnetic tape data.

Table E-3

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: MARBLE-BED SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 330°F	Liquor Flow Rate, gpm		L/G,[g] gal/mcf	Stoichiometric Ratio[a]	Percent Solids Recirculated	EHT[h] Residence Time, min.	Marble Height, in.	Weir Height[b] in.	Pressure Drop. in. H_2O[c]	Inlet SO_2 Conc., ppm	Percent SO_2 Removal
			Top Sprays	Bottom Sprays									
8/21-28	401-3A[d]	20,000	200	410	38	2.15-3.20	5-9	50	5	3	8.0-10.0	1800-2700	56 ± 7
7/9-10	401-3B[d]	20,000	200	395	37	1.90-2.85	4-12				6.6- 8.6	2100-2300	63 ± 5
9/23-26	402-3A	20,000	205	405	38	2.10-2.80	6-10				6.5- 8.5	1700-2300	59 ± 5
9/28-29	403-3A	20,000	200	605	50	1.75-2.05	5-7				8.8-10.8	2500-3100	79 ± 4
9/30-10/1	404-3A	20,000	205	200	25	4.30-4.85	5-7				8.2-10.2	2500-2800	37 ± 6
10/1-3	405-3A	20,000	200	200	25	3.30-3.85	5-7				8.4-10.4	2200-2900	35 ± 6
10/3-6	406-3A	20,000	205	600	50	1.75-2.15	5-7				11.5-13.5	2300-2800	77 ± 6
10/6	407-3A	20,000	205	605	50	1.55-1.95	5-7				13.0-15.0	2500-2900	75 ± 6
10/10-12	408-3A	20,000	200	600	50	2.15-2.65	5-7				10.7-11.7	2500-3000	75 ± 5
10/13-17	409-3A	20,000	205	205	25	4.15-5.85	5-7				8.2- 9.2	2400-2900	30 ± 5
10/17-20	410-3A	20,000	200	605	50	2.05-2.50	5-7				9.5-10.5	3200-2500	68 ± 3
10/20-21	411-3A	20,000	200	200	25	5.30-5.80	4-6				8.8- 9.8	3000-3200	32 ± 5
10/21-22	412-3A	20,000	200	200	25	3.30-4.15	5-7				9.4-10.4	3000-3200	35 ± 5
10/22-23	413-3A	20,000	205	605	50	2.00-2.35	5-7				10.2-11.2	3000-3200	58 ± 3
10/23-24	414-3A	20,000	200	605	50	2.45-2.90	5-7				10.3-11.3	3100-3500	65 ± 5
10/24-25	415-3A	19,900	200	600	50	2.20-2.40	5-7				10.1-11.1	3000-3400	65 ± 3
10/25-27	416-3A	20,000	195	205	25	4.45-5.30	5-7				8.7- 9.7	2800-3200	36 ± 5
10/27-28	418-3A	30,000	205	205	17	7.30-7.70	5-7				8.8- 9.8	3000-3200	24 ± 5
10/29	419-3A	29,900	210	210	18	4.30-4.80	4-6				8.8- 9.8	3100-3300	28 ± 4
10/30-31	417-3A	30,000	205	605	34	1.60-1.85	5-7				12.7-13.9	3100-3300	73 ± 3
10/31-11/1	420-3A	20,000	205	600	50	1.75-2.05	5-7				9.8-11.0	2900-3300	79 ± 3
11/1-2	421-3A	20,000	200	200	25	5.00-5.30	5-7				8.5- 9.5	2900-3100	34 ± 4
11/5	422-3A	20,000	205	605	50	1.55-1.65	11-13				9.0-10.0	3300-3600	75 ± 3
11/8-9	425-3A	30,000	205	605	34	2.60-2.90	10-12				10.0-12.0	3000-3400	66 ± 5

Note: Footnote definitions are on following page.

(continued)

Table E-3 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: MARBLE-BED SYSTEM

Date	Run No.	Gas Flow Rate, acfm @ 330°F	Liquor Flow Rate, gpm		L/G,[g] gal/mcf	Stoichiometric Ratio[a]	Percent Solids Recirculated	EHT[h] Residence Time, min	Marble Height, in.	Weir Height[b] in.	Pressure Drop, in H$_2$O[c]	Inlet SO$_2$ Conc., ppm	Percent SO$_2$ Removal
			Top Sprays	Bottom Sprays									
11/11	426-3A	20,000	200	600	50	1.85-2.00	5-7	50	5	3	9.4-11.4	2600-3100	81±4
11/12-16	427-3A	20,000	205	605	50	1.40-1.90	5-7	↓	↓	↓	11.0-13.0	2500-2900	79±5
11/28	426-3B	20,000	200	610	50	(e)	5-7	↓	↓	↓	8.9-10.9	2800-3200	82±3
12/1-6	427-3C	20,000	200	600	50	↓	5-7	↓	↓	↓	11.9-12.7	2800-3400	78±4
12/20-26	427-3B	20,000	200	605	50	↓	5-7	↓	↓	↓	10.3-12.3	2200-2800	80±2
12/26-1/3	428-3A	20,000	200	610	50	↓	5-7	↓	↓	↓	11.0-12.0	2500-3100	78±4
1/3-4	429-3A	20,000	0	605	37	↓	5-7	↓	↓	↓	9.1-9.9	2600-2800	63±2
1/5-6	431-3A[f]	20,000	0	605	37	↓	5-7	↓	3	↓	4.6-9.1	3000-3300	48-73[f]
1/6-7	433-3A	20,000	0	205	13	↓	5-7	100	↓	↓	5.5-6.7	3000-3400	20±3
1/7-8	438-3A	19,900	0	400	25	↓	5-7	50	↓	↓	6.8-7.2	3300-3500	34±2
1/8-9	439-3A	12,600	0	405	40	↓	5-7	↓	↓	↓	6.0-6.8	3300-3500	49±2
1/9-16	440-3A	12,500	0	600	60	↓	6-8	↓	↓	6	6.6-7.0	2900-3300	60±4
1/20-22	425-3B	30,000	200	600	25	↓	10-14	↓	↓	↓	8.1-8.5	2900-3100	67±2
1/31-2/1	441-3A	20,000	200	605	37	↓	9-11	↓	↓	↓	6.9-7.1	2600-2900	73±2
2/1	442-3A	20,000	0	605	37	↓	7-9	↓	↓	↓	6.8-7.2	2600-2800	69±2

Limestone: Fine ground (87% through 200 mesh), except where noted.

(a) Defined as moles CaCO$_3$ added/mole SO$_2$ absorbed.

(b) Weir height is measured from top of marbles.

(c) Total pressure drop across scrubber, excluding mist eliminator.

(d) Limestone coarse ground (69% through 200 mesh).

(e) Stoichiometries for this period of time are all in excess of 2.0 moles CaCO$_3$/mole SO$_2$ absorbed because of limestone slurry addition problems.

(f) Unstable operation of marble bed.

(g) At scrubber outlet conditions.

(h) Effluent hold tank.

Table E-3 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: MARBLE-BED SYSTEM

Date	Run No.	Gas Temperature, °F			Bed Temp., °F	Liquor Temperature, °F				Ambient Temp., °F	Liquor pH [c]					Turbulent Layer Height, in.
		Hot Gas	Scrubber Inlet	Scrubber Outlet		Top Sprays	Bottom Sprays	Weir Outlet	Down-comer		Top Sprays	Bottom Sprays	Weir Outlet	Down-comer	Clarifier Underflow	
9/21-28	401-3A[a]	315-340	135-145	124-129	119-126	120-125	116-122	119-122	119-125	65-87	6.0-6.3	6.1-6.5	-	5.5-6.2	-	6-8
9/7-10	401-3B[a]	310-340	293-322	120-130	121-125	115-125	112-120	118-122	120-128	60-87	5.8-6.9	6.1-7.0	5.6-5.8	5.7-6.4	6.5-6.6	3-6
9/23-26	402-3A[a]	320-338	301-321	123-130	122-128	120-124	115-121	120-124	120-127	67-77	-	6.0-6.3	5.6-5.8	-	5.9-6.4	7-11
9/28-29	403-3A[a]	310-340	122-319	118-126	110-140	115-122	112-120	118-122	120-125	48-85	6.0-6.2	6.0-6.3	5.6-5.8	5.8-6.0	6.1-6.7	11-17
9/30-10/1	404-3A[a]	310-325	238-313	120-125	116-122	108-111	102-106	114-118	114-118	44-61	5.9-6.2	5.9-6.5	5.4-5.6	5.7-5.8	6.1-6.8	3-5
10/1-3	405-3A[a]	300-340	156-160	125-132	110-122	104-114	102-109	111-118	113-119	53-77	5.9-6.2	6.0-6.5	5.8-5.9	5.6-5.8	6.1-6.9	3-4
10/3-6	406-3A	310-340	145-240	(b)	111-122	117-120	115-119	115-122	120-126	57-80	5.8-6.1	5.8-6.1	5.6-5.8	5.6-5.8	5.9-6.3	10-13
10/6-8	407-3A	310-340	208-216	↓	118-125	116-119	115-118	116-122	121-125	53-80	5.8-5.9	5.8-5.9	5.6-5.8	5.6-5.7	5.9-6.1	12-15
10/10-12	408-3A	320-340	124-133		118-130	115-121	110-120	114-125	116-127	60-75	5.9-6.3	5.8-6.4	5.6-6.1	5.7-5.9	6.1-6.5	11-17
10/13-17	409-3A	315-338	124-133		121-123	110-116	105-110	116-122	115-120	58-76	5.7-6.3	5.8-6.3	5.7-5.9	5.4-6.2	6.1-6.5	3-5
10/17-20	410-3A	303-321	(b)		93-123	97-114	108-114	115-121	117-126	38-50	6.1-6.2	6.3-6.5	5.6-5.7	5.7-5.9	6.1-6.5	7-9
10/20-21	411-3A	310-325			115-120	108-111	100-105	111-120	111-120	46-56	6.1-6.4	6.7	5.4-5.5	6.0	6.4-6.8	1-3
10/21-22	412-3A	315-330	↓		118-121	113-115	104-109	117-120	116-120	57-67	6.2-6.4	6.2-6.6	5.7-5.8	5.6-5.7	6.6-6.8	2-3
10/22-23	413-3A	310-338			122-130	116-118	111-115	116-120	117-125	59-65	6.1-6.2	6.1-6.2	5.6	5.7-5.8	6.4-6.8	11-13
10/23-24	414-3A	317-321			122-127	112-116	111-114	115-119	121-123	47-56	6.0-6.1	6.1-6.2	5.6-5.7	5.7-5.8	6.3-6.5	7-9
10/24-25	415-3A	315-324			111-123	106-115	108-113	113-119	118-125	46-51	6.0-6.1	6.0-6.3	5.6-5.7	5.7-5.8	6.4-6.6	5-9
10/25-27	416-3A	308-319			115-124	107-112	99-104	114-120	113-119	37-59	6.1-6.2	6.2-6.3	5.5-5.7	5.7-5.8	6.4-6.8	2-3
10/27-28	418-3A	319-335			121-125	111-113	100-104	116-122	116-125	53-59	6.0-6.1	6.1-6.2	5.6-6.2	5.5-5.9	6.3-6.6	2-5
10/28	419-3A	318-325			119-124	111-115	103-110	117-121	118-123	52-59	5.9-6.1	6.1-6.3	5.4	5.4	6.3-6.4	3-5
10/30-31	417-3A	320-330			110-140	110-115	110-115	110-120	115-122	54-61	5.6-5.9	5.8-6.0	5.0-5.2	5.1-5.5	6.1-6.3	19-21
10/31-11/1	420-3A	308-335			120-128	115-118	114-117	116-121	115-125	63-73	5.6-6.1	5.8-6.1	5.0-5.8	5.1-5.8	6.1-6.5	14-18
11/1-2	421-3A	320-340			112-125	104-115	101-107	114-119	113-117	52-81	6.1-6.2	6.1-6.2	5.3-5.4	5.6	6.4-6.5	2-4
11/8	422-3A	280-320			97-124	99-115	108-115	113-119	117-122	40-61	6.0-6.3	6.2-6.3	5.4-6.2	5.6-6.1	6.3-6.5	8-9
11/8-9	423-3A	310-325			115-124	106-113	99-114	115-120	120-126	43-56	6.0-6.1	6.0-6.1	5.8-6.0	5.7-5.8	6.3-6.4	10-15

Note: Footnote definitions on following page.

(continued)

Table E-3 (continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: MARBLE-BED SYSTEM

Date	Run No.	Gas Temperature, °F			Bed Temp., °F	Liquor Temperature, °F				Ambient Temp., °F	Liquor pH (c)					Turbulent Layer Height, in.
		Hot Gas	Scrubber Inlet	Scrubber Outlet		Top Sprays	Bottom Sprays	Weir Outlet	Down-comer		Top Sprays	Bottom Sprays	Weir Outlet	Down-comer	Clarifier Underflow	
11/11	426-3A	310-320	(b)	(b)	118-121	76-111	74-110	72-114	110-120	48-49	6.0-6.2	5.9-6.1	5.7-5.9	5.6	6.5-6.7	10-19
11/12-16	427-3A	295-320	↓	↓	122-135	111-118	112-118	115-120	121-126	44-61	6.0-6.1	6.1-6.5	5.9-6.0	5.9	6.3-6.7	9-18
11/28	426-3B	314-317			94-107	92-99	93-106	112-128	111-122	37-40	6.0-6.3	6.2-6.4	5.9-6.0	5.8	6.9-7.0	10-11
12/1-6	427-3C	310-325			116-128	115-118	113-120	118-120	115-120	40-60	6.0-6.3	6.4-6.8	6.1-6.2	6.0-6.2	6.6-7.0	16-19
12/20-26	427-3B	290-300		115-120	118-125	100-110	105-112	113-117	115-125	32-42	5.9-6.2	6.0-6.2	5.6-6.0	5.6-6.0	6.4-6.5	13-16
12/26-1/3	428-3A	290-315		112-118	105-113	102-108	101-108	108-111	115-119	35-50	6.0-6.2	6.1-6.2	5.8-6.0	5.6-6.1	6.2-6.4	9-11
1/3-4	429-3A	305-320		116-122	112-119	—	107-111	110-118	119-123	41-45	—	6.2-6.3(a)	—	—	—	3-4
1/5-6	431-3A	292-316		110-121	115-152	—	71-91	104-118	93-105	21-27	—	6.2	5.8	—	7.1	0-3
1/6-7	433-3A	299-314		114-122	114-139	—	66-77	89-114	92-103	26-29	—	6.5	—	—	7.2	2-9
1/7-8	438-3A	295-313		115-124	113-125	—	71-85	106-118	85-104	25-29	—	6.1	—	—	7.3	2-8
1/8-9	439-3A	285-301		110-118	104-113	—	71-95	106-112	77-93	20-26	—	6.3	—	—	7.4	0-5
1/9-16	440-3A	284-322		110-119	106-119	—	63-107	106-114	71-114	14-48	—	6.2-6.6	5.9-6.3	6.1-6.3	7.4-7.8	2-9
1/20-22	425-3B	305-320		113-128	118-129	90-117	97-116	108-121	117-127	35-53	5.9-6.2(a)	6.0-6.2	—	—	—	11-22
1/31-2/1	441-3A	302-320		118-123	113-120	95-112	107-114	112-118	115-122	46-65	6.1-6.2(a)	6.1-6.4(a)	—	—	—	6-19
2/1	442-3A	314-335	↓	119-124	118-126	—	110-114	112-128	116-122	50-66	—	6.2-6.3(a)	—	—	—	9-16

(a) pH's taken from in-line meters.

(b) Digital output in error.

(c) Single values indicate only one pH reading taken.

Table E-4

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: SPRAY TOWER

Date	Run No.	Gas Flow Rate, acfm @ 330°F	Liquor Flow Rate,[a] gpm	L/G,[d] gal/mcf	Stoich. Ratio, moles Ca added/ mole SO_2 abs.	Percent Solids Recirculated	EHT[e] Residence Time, min.	Pressure Drop,[b] in. H_2O	Inlet SO_2 Concentration, ppm	SO_2 Removal, %	No. Spray Headers Used[c]
9/13-14	523-1A	30,000	910	37	2.4	12.2	27	3.6	3100-3300	51 ±1	4
9/14	520-1A	30,000	1195	50	1.9	12.4	20	4.0	2900-3300	68 ±2	4
9/14	524-1A	25,100	1210	60	2.0	12.5	18	3.1	3200-3300	68 ±1	4
9/14	526-1A	17,500	1195	85	2.1	12.0	18	1.7	3000-3200	74 ±1	4
9/14	521-1A	29,900	905	37	2.1	11.6	24	3.2	3000-3100	50 ±1	3 (1, 3, 4)
9/14-15	527-1A	17,500	905	64	1.9	11.1	24	1.5	3000-3200	66 ±1	3 (1, 3, 4)
9/15	522-1A	30,000	600	25	2.1	11.2	35	3.3	3200-3500	43 ±2	2 (3, 4)
9/15	525-1A	25,000	600	30	2.4	11.5	35	2.6	3200-3500	45 ±1	2 (3, 4)
9/15	528-1A	17,400	600	43	2.0	11.4	35	1.2	2900-3000	52 ±1	2 (3, 4)
9/15	529-1A	29,900	1185	50	2.0	11.2	18	4.0	2900-3300	63 ±1	4
9/15-16	530-1A	25,000	890	45	1.8	10.5	24	2.5	3300-3400	54 ±2	3 (1, 3, 4)
9/16	531-1A	30,000	890	37	2.4	10.7	24	3.8	3200-3300	56 ±1	3 (1, 3, 4)
9/16	532-1A	29,900	585	24	2.3	11.1	35	3.1	3200-3500	41 ±1	2 (3, 4)

Note: Footnote definitions are on the following page

Table E-4 (Continued)

TEST RESULTS FROM LIMESTONE FACTORIAL RUNS: SPRAY TOWER

Date	Run No.	Gas Temperature, °F			Liquor Temperature, °F		Ambient Temp., °F	Liquor pH	
		Hot Gas	Venturi Inlet	Spray Tower	Tower Inlet	Tower Outlet		EHT[e] Outlet	Tower Outlet
9/13-14	523-1A	337-342	128-131	127-131	124-126	126-129	68-70	5.9	5.3-5.5
9/14	520-1A	327-345	124-135	125-132	↓	↓	68-70	6.0	5.5-5.6
9/14	524-1A	328-335	129-132	127-131			69-71	6.0-6.1	5.6
9/14	526-1A	325-335	125-132	126-131			69-74	6.1	5.6-5.8
9/14	521-1A	336-345	127-132	127-132			69-74	5.8	5.2
9/14-15	527-1A	314-342	123-131	124-129			65-68	5.9	5.2-5.5
9/15	522-1A	318-337	126-132	124-130			62-64	5.9-6.0	5.2
9/15	525-1A	326-337	125-132	126-132			64-80	6.0-6.1	5.2
9/15	528-1A	327-334	121-123	125-128			81-83	5.9-6.0	5.2-5.3
9/15	529-1A	340-351	124-132	126-132			69-82	5.8	5.1-5.2
9/15-16	530-1A	330-339	126-128	124-126			63-69	5.8	5.2-5.3
9/16	531-1A	322-328	124-130	124-127			58-62	5.9	5.1-5.2
9/16	532-1A	329-344	126-130	126-128			64-89	5.8	5.0-5.1

(a) 10 gpm of water was used in venturi saturation sprays. No slurry flow to venturi (venturi plug 100% open).

(b) Pressure drop across the spray tower, excluding mist eliminator.

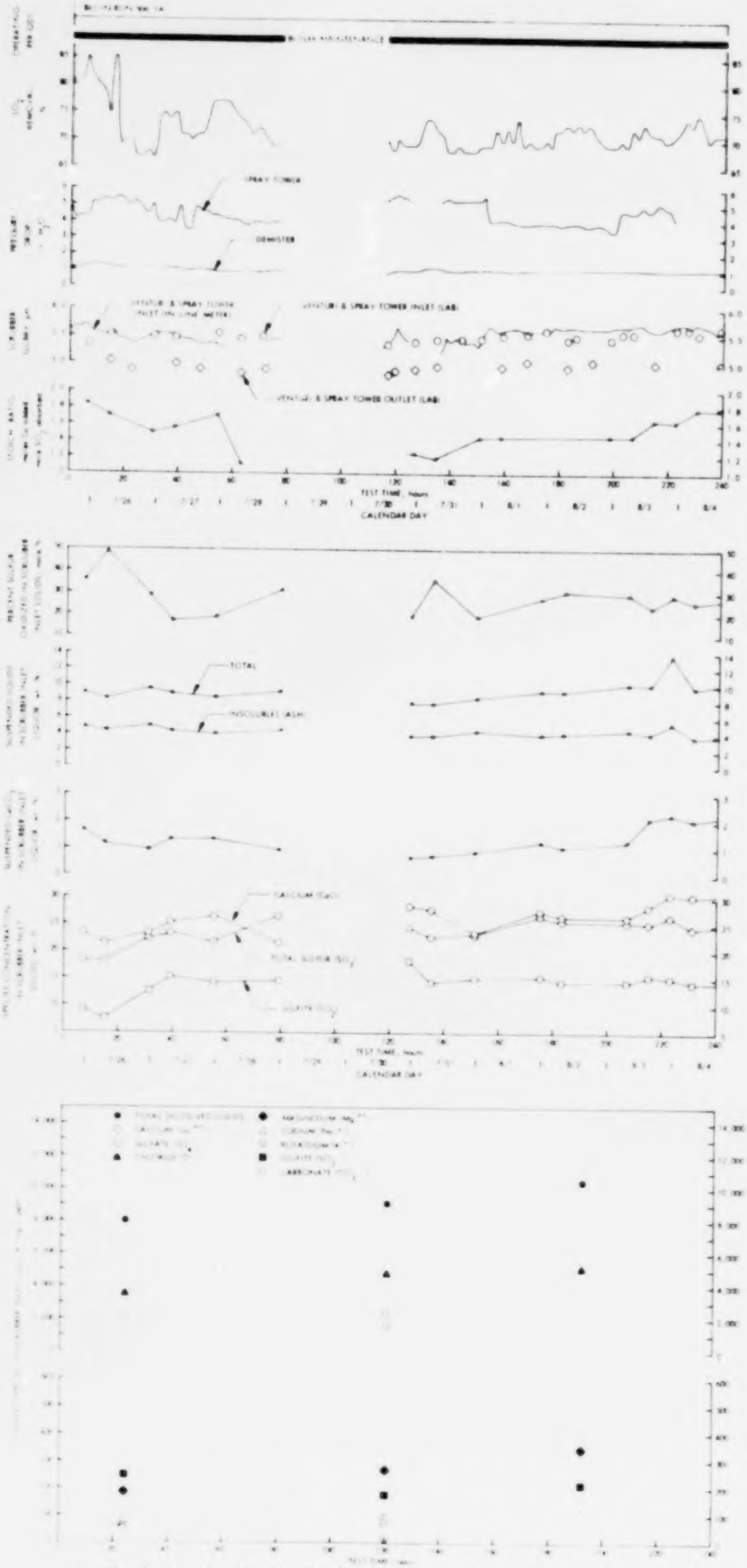
(c) Numbers in parentheses refer to header positions, counting from bottommost header.

(d) At scrubber conditions.

(e) Effluent hold tank.

Appendix F

SELECTED GRAPHICAL OPERATING DATA FROM LIMESTONE RELIABILITY VERIFICATION TESTS

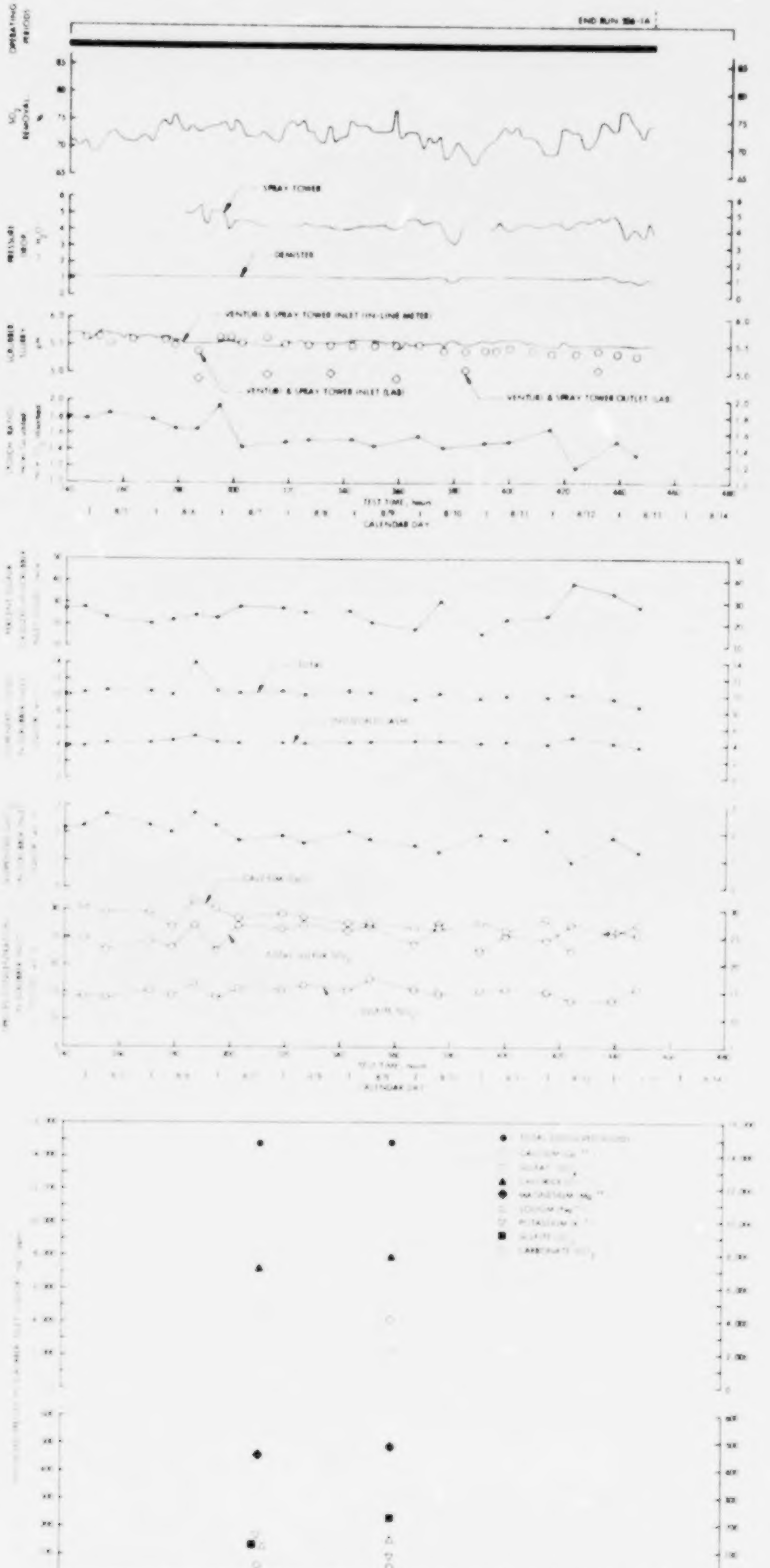


Gas Rate: 30,000 acfm @ 330 °F
Liquor Rate to Venturi: 600 gpm
Liquor Rate to Spray Tower: 1,200 gpm
Venturi L/G: 27 gal/mcf
Spray Tower L/G: 53 gal/mcf
Spray Tower Gas Velocity: 7.5 ft/sec
Venturi Pressure Drop: 9 in H_2O
E.H.T. Residence Time: 12 min
No. of Spray Headers: 4

Gas Inlet SO_2 Conc.: 2,500-3,200 ppm
(2,000-2,200 ppm during 7/26 and 7/28)
Scrubber Inlet Liquor Temp.: 126-131 °F
Liquid Conductivity: 9,500-21,500 µ mhos/cm
Discharge (Clarifier & Centrifuge) Solids
Conc.: 57-65 wt %

Note: As of July 27, a limestone containing approximately 1 1/4 mole % $MgCO_3$ has been used at the test facility. Prior to this time a limestone having approximately 5 mole % $MgCO_3$ has been used.

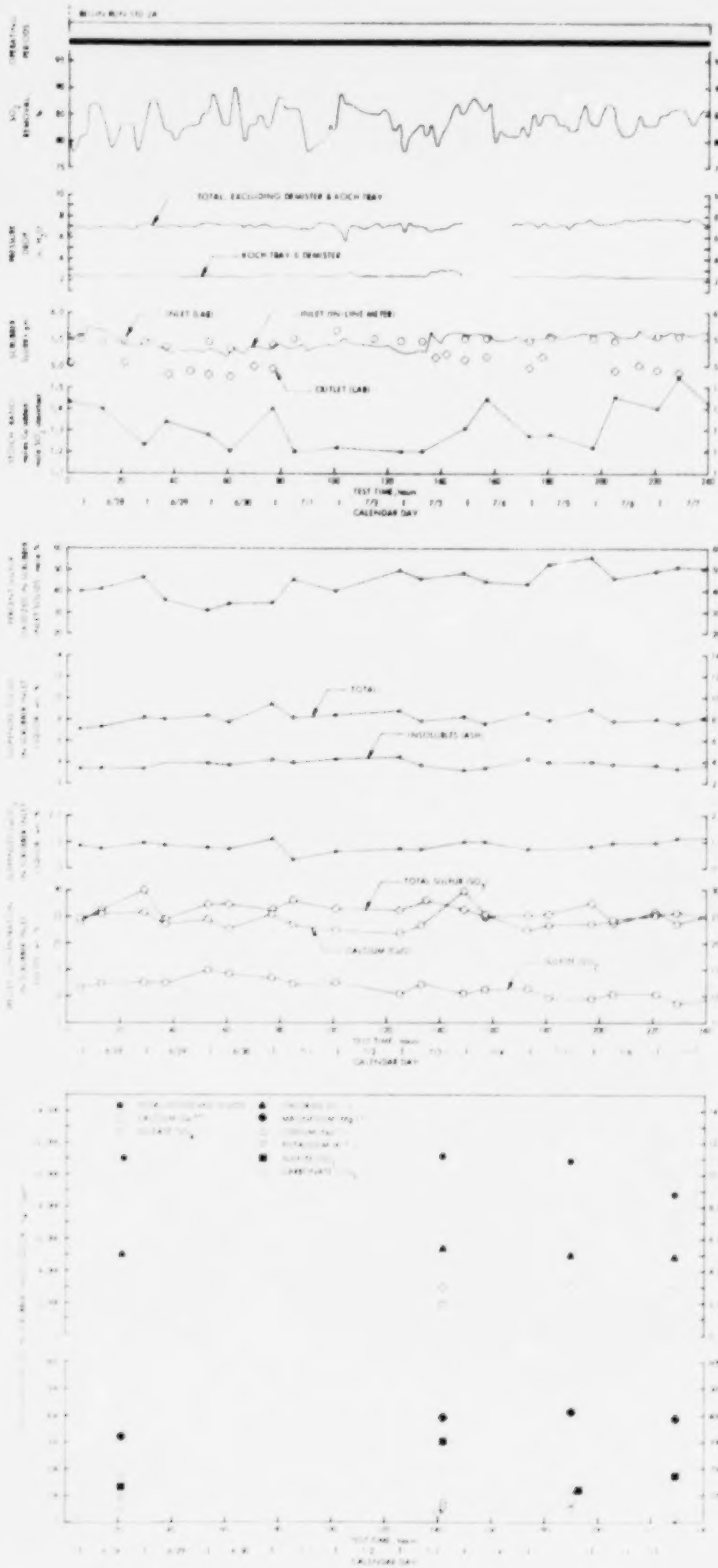
Figure F-1
OPERATING DATA FOR
VENTURI/SPRAY TOWER
RUN 506-1A



Gas Rate = 30,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1,200 gpm
Venturi L/G = 27 gal/mcf
Spray Tower L/G = 53 gal/mcf
Spray Tower Gas Velocity = 7.5 ft/sec
Venturi Pressure Drop = 9 in H_2O
E.H.T. Residence Time = 12 min
No. of Spray Headers = 4

Gas Inlet SO_2 Conc. = 2,600-3,300 ppm
Scrubber Inlet Liquor Temp. = 128-132 °F
Liquid Conductivity = 22,000-27,000 μ mhos/cm
Discharge (Clarifier & Centrifuge) Solids
Conc. = 55-65 wt %

Figure F-1 (Continued)
OPERATING DATA FOR
VENTURI/SPRAY TOWER
RUN 506-1A



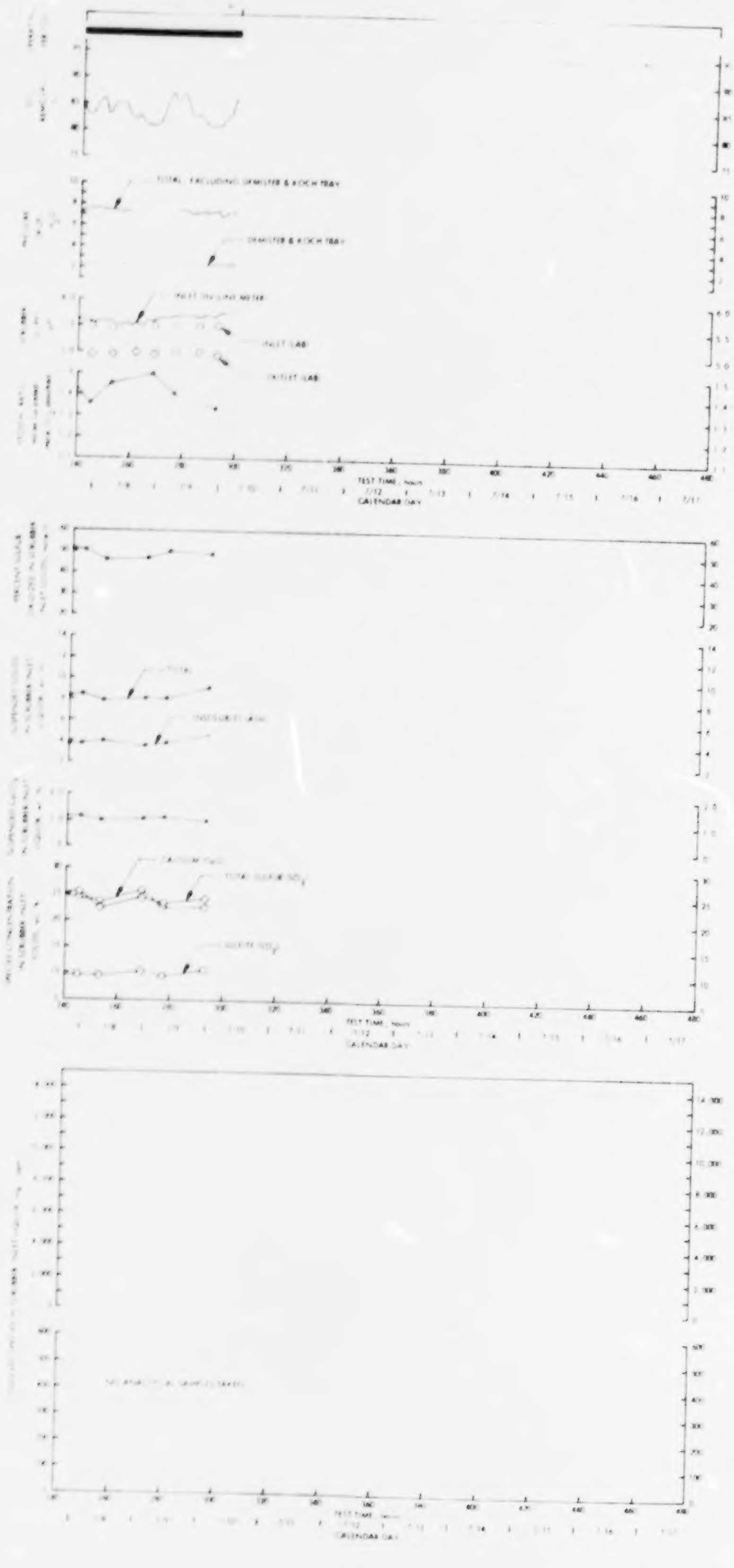
Gas Rate = 25,000 acfm @ 300 °F
Liquor Rate = 1,200 gpm
L/G = 64 gal/mcf
Gas Velocity = 9.8 ft/sec
E.H.T. Residence Time = 20 min
Three Stages, 5 in spheres/stage

Gas Inlet SO_2 Conc = 2,000-2,700 ppm
Scrubber Inlet Liquor Temp = 121-127 °F
Liquid Conductivity = 11,000-20,000 µ mhos/cm
Discharge (Clarifier) Solids Conc = 26-44 wt %

Figure F-2

OPERATING DATA FOR TCA

RUN 510-2A



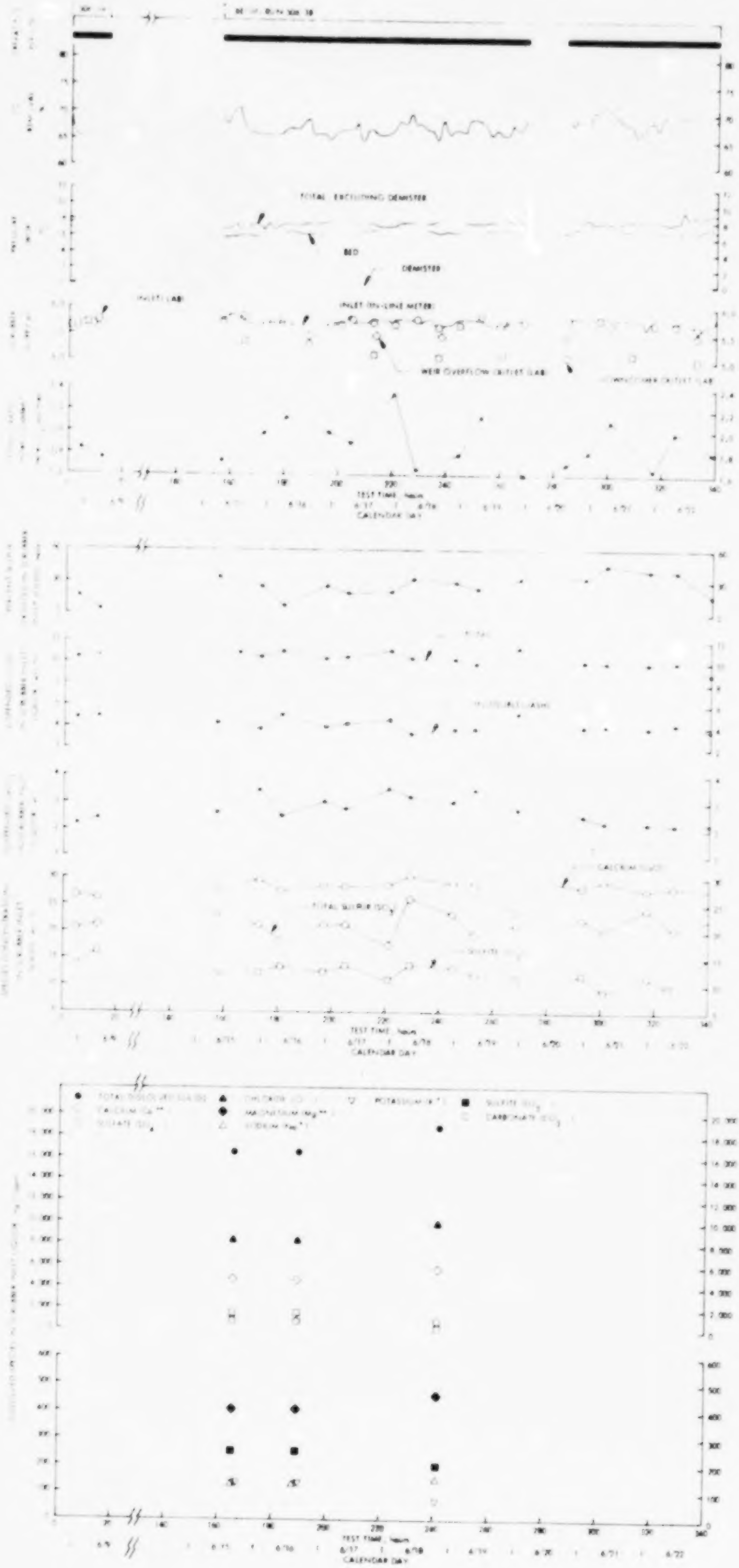
Gas Rate: 25,000 acfm @ 300°F
Liquor Rate: 1,200 gpm
L/G: 64 gal/mcf
Gas Velocity: 9.8 ft/sec
E.H.T. Residence Time: 20 min
Three Stages, 5 in. spheres/stage

Gas Inlet SO_2 Conc: 2,200-2,600 ppm
Scrubber Inlet Liquor Temp: 123-127°F
Liquid Conductivity: 18,000-22,400 µ mhos/cm
Discharge (Clarifier) Solids Conc: 36-38 wt %

Figure F-2 (Continued)

OPERATING DATA FOR TCA

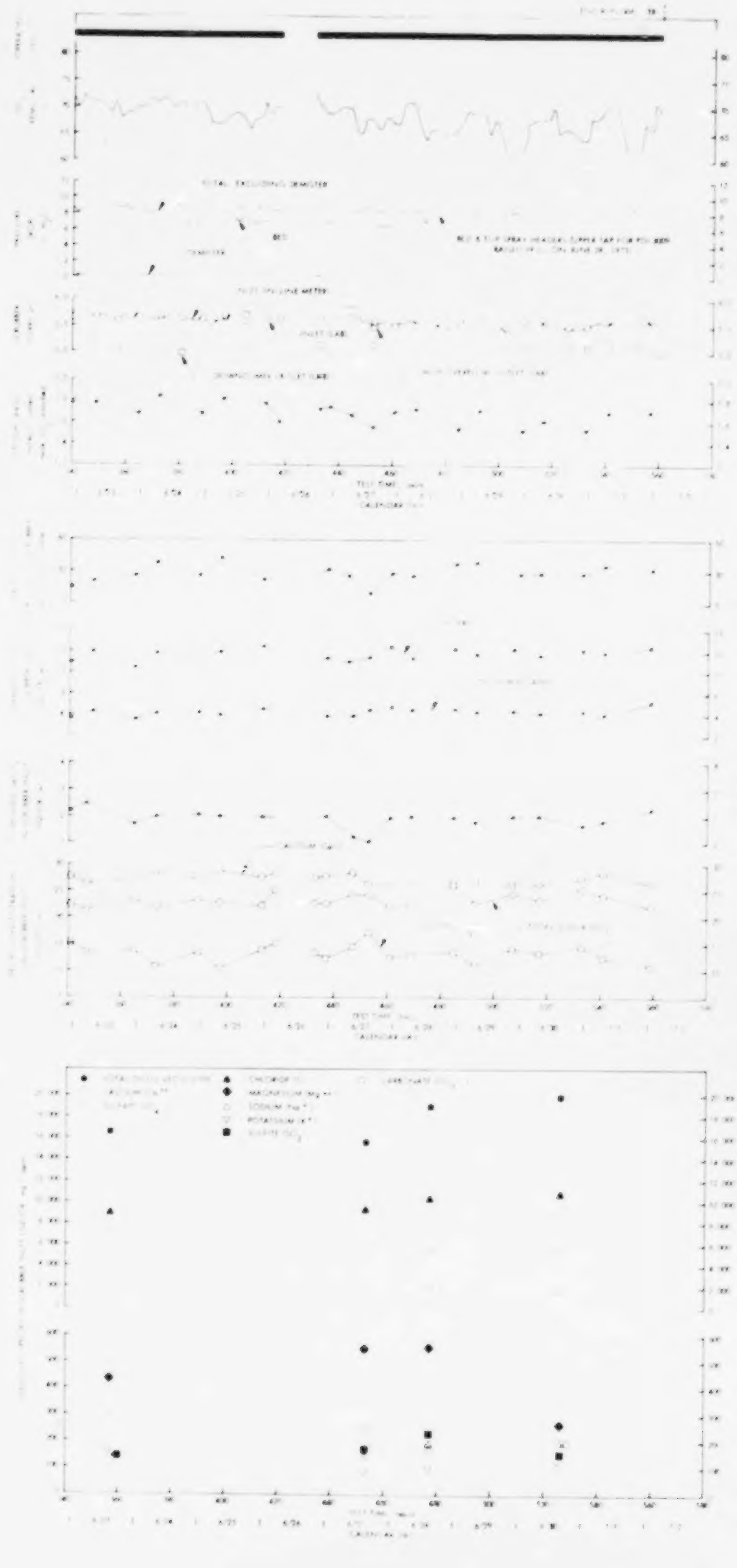
RUN 510-2A



Gas Rate 20,000 acfm (@ 300°F)
Liquid Rate 800 gpm (total)
L/G 53 gal/mcf
Gas Velocity 5.1 ft/sec
E.H.T. Residence Time 30 min
Marble Bed Height 3.5 in.

Gas Inlet SO_2 Conc. 2,300-3,100 ppm
Scrubber Inlet Liquid Temp 122-129 °F
Liquid Conductivity 23,000-32,000 μ mhos/cm
Discharge (Centrifuge) Solids Conc. 60-66 wt %

Figure F-3
OPERATING DATA FOR
MARBLE-BED
RUN 506-3A & 3B



Gas Rate 20,000 acfm @ 130 °F
Liquid Rate [illegible] gpm
L/G 5.3 gal/mcf
Gas Velocity 5.1 ft/sec
E.H.T. Residence Time 30 min
Marble Bed Height 3.5 in

Gas Inlet SO_2 Conc. 2,100-3,200 ppm
Scrubber Inlet Liquid Temp. 122-130 °F
Liquid Conductivity 25,000-30,500 μ mhos/cm
Discharge (Centrifuge) Solids Conc. 60-66 wt

Figure F-3 (Continued)
OPERATING DATA FOR
MARBLE-BED
RUN 506-3A & 3B

Appendix G

BECHTEL MODIFIED RADIAN EQUILIBRIUM COMPUTER PROGRAM

INTRODUCTION

The Bechtel Modified Radian Equilibrium Computer Program takes as input the measured composition (g-mole/liter or ppm) and pH (optional) of an aqueous liquor or slurry containing dissolved Ca, Mg, Na, K, SO_3, SO_4, CO_3, and Cl species. The partial pressures of CO_2 and SO_2 in equilibrium with the liquid may be input instead of the concentrations of carbonate and sulfite species.

The program determines:

- Presence or absence of solid species ($CaCO_3$, $CaSO_3$, $CaSO_4$, $Ca(OH)_2$, $MgCO_3$, $Mg(OH)_2$)
- Concentrations and activities of individual dissolved ionic and molecular species
- Liquid pH (if unspecified)
- Ionic imbalance of dissolved species (if pH is specified)
- Equilibrium partial pressures of CO_2 and SO_2 gases above the liquid (if unspecified)
- Degree of $CaSO_4 \cdot 2H_2O$ saturation of liquid

For the program, the following sections of this appendix present:

- SUBPROGRAM DESCRIPTIONS

  Includes file type and function for each subprogram

- PROGRAM INPUTS

  Shows the order of input data in data file

- TERMINAL RECORD

  Gives example test cases showing the creation of input data file and equilibrium program output

- PROGRAM LISTINGS

SUBPROGRAM DESCRIPTIONS

Filename	Filetype	Function
BEQCALL	FORTRAN IV (G)	CSS* main program FORTRAN file reads input data and calls BEQ.
BEQ	FORTRAN IV (G)	Modified Radian program; determines aqueous solution equilibria for the slurry system Ca, Mg, Na, K, SO_2, SO_3, CO_2, Cl.
BEQCON	FORTRAN IV (G)	Calculates equilibrium constants in BEQ.
BEQSOX	FORTRAN IV (G)	Handles special cases of SO_3 and SO_4 solids not covered by BEQ.
BEQPRINT	FORTRAN IV (G)	Prints output from BEQ.
BEQ	EXEC	CSS* executive program for operating BEQ.
BEQ	DATA	Input data file for BEQ.

---

*These files have been written for use only on the National CSS, Inc., time-sharing system.

PROGRAM INPUTS

Data is input to the modified Radian equilibrium computer program (BEQ FORTRAN) through a BEQ DATA file. The format for this file is:

Line 1: Identification statement (up to 80 alphanumeric characters)

Line 2: JPRINT, JCONC, JS, TK, $ppSO_2$, $ppCO_2$, SSO_3, SSO_4, IPH, PH

Line 3: Ca, Mg, Na, K, SO_3, SO_4, CO_3, Cl

Where:

JPRINT = Print flag = 1 or 2
JCONC = Concentration flag = 1 or 2
JS = Solids flag = 0 or 1
TK = Liquor temperature, ^{o}K
$ppSO_2$ = Partial pressure SO_2, atm
$ppCO_2$ = Partial pressure CO_2, atm
SSO_3 = Relative sulfite saturation
SSO_4 = Relative sulfate saturation
IPH = pH flag = 0 or 1
PH = Liquor pH

$$\left.\begin{array}{l} \text{Ca} \\ \text{Mg} \\ \text{Na} \\ \text{K} \\ SO_3 \\ SO_4 \\ CO_3 \\ \text{Cl} \end{array}\right\} = \text{total amount of component (solid plus liquid) in slurry, gmole/liter liquid or ppm}$$

JPRINT - Print Flag

JPRINT = 1 Use for long-form printout
= 2 Use for short-form printout

JCONC - Concentration Flag

JCONC = 1 Concentrations are input in ppm
= 2 Concentrations are input in gmole/liter liquid

JS - Solids flag

JS = 0 Use when no solids are present (i.e., program assumes all input species are in liquid). This permits program to predict the sulfate saturation of the liquor.

= 1 Use when there is the possibility of solids being present. When JS = 1, the partial pressure of CO_2, $ppCO_2$, must be specified rather than the total CO_3 in the slurry.

$ppSO_2$, $ppCO_2$ - Partial Pressure

Set pp SO_2 = 0 if SO_3 in slurry is specified. Set $ppCO_2$ = 0 if CO_3 in slurry is specified. When JS = 1, $ppCO_2$ must be specified rather than CO_3. When JS = 0, either $ppCO_2$ or CO_3 can be specified.

SSO_3, SSO_4 - Relative Saturation

Set SSO_3 = 1 and SSO_4 = 1 (100% saturation) for normal Radian equilibrium. Use of other values permits the program to predict up to the specified degree of SO_3 or SO_4 saturation before formation of solids (e.g., a value of SSO_4 = 1.4 allows for a SO_4 saturation of 140%). The JS = 0 flag overrides the specified values of SSO_3 and SSO_4.

IPH, PH - Liquor pH

IPH = 0 pH is not specified
= 1 pH is specified

PH = Specified liquor pH

If the pH is specified (e.g.: the measured pH of a liquor sample), the ionic balance equation is discarded from the program, and the ionic imbalance is printed out. For limestone and lime wet scrubbing liquids it is generally better to input the pH when it is known.

SO_3 and CO_3 Concentrations

Set $SO_3 = 0$ if $ppSO_2$ is specified. Set $CO_3 = 0$ if $ppCO_2$ is specified. When JS = 1, $ppCO_2$ must be specified rather than CO_3.

TERMINAL RECORD

CREATION OF INPUT DATA FILE
AND EQUILIBRIUM PROGRAM OUTPUT

IBM 2741 Terminal
Input in Lower Case
Terminal Response in Upper Case

← CREATE INPUT DATA FILE

```
17.02.28 >edit beq data
NEW FILE.
INPUT:
>Sample point 2816    4/12/74 at 0800
>1, 1, 0, 323, 0, 0, 1, 1, 1, 5.75
>1812, 333, 51, 118, 72, 1806, 358, 2801
>Sample point 2816    4/12/74 at 0800
>2, 2, 0, 323, 0, 0, 1, 1, 1, 5.75
>0.00452, 0.01370, 0.00222, 0.00302, 0.00090, 0.01330, 0.00597, 0.02901
>Sample point 2816    4/12/74 at 0800
>1, 1, 1, 323, 0, 0.2151, 1, 1, 0
>1812, 333, 51, 118, 72, 1806, 0, 2801

EDIT:
>file
```

← PRINT FILE

```
17.08.18 >print beq data
```

Case 1

```
SAMPLE POINT 2816    4/12/74 AT 0800
1, 1, 0, 323, 0, 0, 1, 1, 1, 5.75
1812, 333, 51, 118, 72, 1806, 358, 2801
```

Case 2

```
SAMPLE POINT 2816    4/12/74 AT 0800
2, 2, 0, 323, 0, 0, 1, 1, 1, 5.75
0.00452, 0.01370, 0.00222, 0.00302, 0.00090, 0.01330, 0.00597, 0.0290
```

Case 3

```
SAMPLE POINT 2816    4/12/74 AT 0800
1, 1, 1, 323, 0, 0.2151, 1, 1, 0
1812, 333, 51, 118, 72, 1806, 0, 2801
```

← EXECUTE PROGRAM

```
17.08.43 >beq
EXECUTION>
```

NOTE:

Case 1 - LONG-FORM PRINTOUT
NO SOLIDS (JS = 0)

Case 2 - SHORT-FORM PRINTOUT
OF CASE 1

Case 3 - LONG-FORM PRINTOUT
SOLIDS (JS = 1)

Case 1

```
     SAMPLE POINT 2816    4/12/74 AT 0800

                                   BECHTEL MODIFIED RADIAN EQUILIBRIUM PROGRAM
 INPUT DATA:
    K1     JS     TK      PPSO2         PPCO2          SSO3      SSO4    IPH    PH
    1      0    323.0  0.0           0.0             1.000     1.000     1   5.750

   CONCENTRATIONS, GMOL/LITER AND PPM(WT):
       CA        MG        NA         K         SO3        SO4        CO3        CL
 0.04521   0.01370   0.00222   0.00302   0.00090   0.01880   0.00597   0.07901
   1812.      333.       51.      118.       72.     1806.       358.     2801.

 CALCULATED RESULTS:             CONCENTRATION
              COMPONENT          GMOL/LITER            ACTIVITY COEFFICIENT

              H+                 0.2162E-05               0.8227
              OH-                0.4101E-07               0.7450
              H2CO3              0.3913E-02               1.0287
              HCO3-              0.1593E-02               0.7336
              CO3--              0.1527E-06               0.2896
              H2SO3              0.8066E-07               1.0287
              HSO3-              0.4993E-03               0.7336
              SO3--              0.3037E-04               0.2896
              HSO4-              0.1088E-05               0.7450
              SO4--              0.9145E-02               0.2423
              CA++               0.3734E-01               0.3137
              CAOH+              0.1338E-07               0.7450
              CAHCO3+            0.3995E-03               0.7450
              CACO3              0.1060E-05               1.0287
              CASO3              0.3374E-03               1.0287
              CASO4              0.7132E-02               1.0287
              MG++               0.1116E-01               0.3081
              MGOH+              0.7375E-07               0.7450
              MGHCO3+            0.5634E-04               0.7450
              MGCO3              0.4986E-06               1.0287
              MGSO3              0.3167E-04               1.0287
              MGSO4              0.2452E-02               1.0287
              NA+                0.5163E-02               0.7578
              NAOH               0.3128E-10               1.0287
              NAHCO3             0.2494E-05               1.0287
              NACO3-             0.5150E-08               0.7450
              NASO4-             0.7060E-04               0.7450
              CL-                0.7901E-01               0.7237

 PH =  5.750         PPSO2 = 0.1540E-05 ATM         PPCO2 = 0.2150      ATM

 PERCENT ERROR IN IONIC BALANCE =     2.5

 PERCENT SULFATE SATURATION =  117.7          ( KSP = 0.2206E-04 )

 TOTAL DISSOLVED SOLIDS =     7351. PPM

 ANALYSIS OF SLURRY:                LIQUID                          SOLID
                                    GMOL/LITER        PPM       GMOL/LITER              PPM
                           CA        0.4521E-01      1812.        0.0                    0.
                           MG        0.1370E-01       333.        0.0                    0.
                           NA        0.2218E-02        51.        0.0                    0.
                           K         0.3018E-02       118.        0.0                    0.
                           SO3       0.8993E-03        72.        0.0                    0.
                           SO4       0.1880E-01      1806.        0.0                    0.
                           CO3       0.5966E-02       358.        0.0                    0.
                           CL        0.7901E-01      2801.        0.0                    0.
```

Case 2

```
     SAMPLE POINT 2B16    4/12/74 AT 0800

                                     BECHTEL MODIFIED RADIAN EQUILIBRIUM PROGRAM
 INPUT DATA:
    K1     JS     TK      PPSO2          PPCO2         SSO3      SSO4    IPH    PH
    2      0    323.0   0.0             0.0           1.000     1.000    1    5.750

   CONCENTRATIONS, GMOL/LITER AND PPM(-T):
      CA        MG        NA         K       SO3        SO4        CO3        CL
 0.04521   0.01370   0.00222   0.00302   0.00090   0.01880   0.00597   0.07901
   1812.      333.       51.      118.       72.     1806.       358.     2801.

PH =  5.750         PPCO2 = 0.2151     ATM

PERCENT ERROR IN IONIC BALANCE =    2.5

PERCENT SULFATE SATURATION =  117.7

TOTAL DISSOLVED SOLIDS =    7351. PPM
```

Case 3

```
SAMPLE POINT 2816     4/12/74 AT 0800

                                     BECHTEL MODIFIED RADIAN EQUILIBRIUM PROGRAM
INPUT DATA:
  KI     JS      TK        PPSO2            PPCO2          SSO3        SSO4     IPH     PH
  1      1    323.0  0.0                 0.2151           1.000       1.000       0    0.0

  CONCENTRATIONS, GMOL/LITER AND PPM(WT):
     CA        MG        NA         K        SO3        SO4       CO3        CL
0.04521   0.01370   0.00222   0.00302   0.00090   0.01880   0.0        0.07901
 1812.      333.       51.      118.       72.     1806.          0.    2801.

CALCULATED RESULTS:              CONCENTRATION
                COMPONENT        GMOL/LITER         ACTIVITY COEFFICIENT

                H+               0.1127E-05              0.8226
                OH-              0.7622E-07              0.7486
                H2CO3            0.3923E-02              1.0267
                HCO3-            0.3033E-02              0.7387
                CO3--            0.5459E-06              0.2977
                H2SO3            0.3072E-07              1.0267
                HSO3-            0.3613E-03              0.7387
                SO3--            0.4124E-04              0.2977
                HSO4-            0.5032E-06              0.7486
                SO4--            0.7855E-02              0.2513
                CA++             0.3485E-01              0.3208
                CAOH+            0.2435E-07              0.7486
                CAHCO3+          0.7276E-03              0.7486
                CACO3            0.3726E-05              1.0267
                CASO3            0.4511E-03              1.0267
                CASO4            0.6073E-02              1.0267
                MG++             0.1128E-01              0.3141
                MGOH+            0.1450E-06              0.7486
                MGHCO3+          0.1109E-03              0.7486
                MGCO3            0.1893E-05              1.0267
                MGSO3            0.4568E-04              1.0267
                MGSO4            0.2256E-02              1.0267
                NA+              0.5168E-02              0.7616
                NAOH             0.6042E-10              1.0267
                NAHCO3           0.4830E-05              1.0267
                NACO3-           0.1895E-07              0.7486
                NASO4-           0.6294E-04              0.7486
                CL-              0.7901E-01              0.7242
                CACO3 (S)        0.5481E-03              1.0000
                CASO4 (S)        0.2553E-02              1.0000

PH =  6.033         PPSO2 = 0.5853E-07 ATM          CO2 =  0.008353 GMOL/L

PERCENT SULFATE SATURATION =  100.0          ( KSP = 0.2206E-04 )

TOTAL DISSOLVED SOLIDS =     7092. PPM

ANALYSIS OF SLURRY:              LIQUID                          SOLID
                                 GMOL/LITER          PPM         GMOL/LITER           PPM
                       CA        0.4211E-01         1688.         0.3101E-02          124.
                       MG        0.1370E-01          333.         0.0                   0.
                       NA        0.2217E-02           51.         0.0                   0.
                       K         0.3014E-02          118.         0.0                   0.
                       SO3       0.8994E-03           72.         0.0                   0.
                       SO4       0.1625E-01         1561.         0.2553E-02          245.
                       CO3       0.7805E-02          468.         0.5481E-03           33.
                       CL        0.7901E-01         2801.         0.0                   0.
```

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PROGRAM LISTINGS

```fortran
C***********************************************************************
C****** THIS ROUTINE CALLS BEQ TO DETERMINE AQUEOUS
C       SOLUTION EQUILIBRIA FOR THE SYSTEM CA,MG,NA,K,SO3,SO4,CO3,CL.
C       (NITRATES ASSUMED ZERO FOR INPUT/OUTPUT CONVENIENCE)
C
C****** FOR JS=1 AND SPECIFIED PPCO2, SOLIDS ARE ALSO DETERMINED.
C
C          PROGRAM USES "BEQ EXEC".
C**********************************************************************
      DIMENSION X(50),CM(10),PP(2),SS(3),XMW(10)
      COMMON /ID/IDENT(20), CCM(10), CW(10)
      COMMON /INPUT/ PPSO2, PPCO2, SS1, SS3, KK1, JJS, PPH
      REAL*8 CMP(10) /'CA++', 'MG++', 'NA+', 'K+', 'SO3--',
     1 'SO4', 'CO3', 'CL-', ' ', ' '/
      REAL*8 DATE, HMS
      DATA XMW /40.08,24.31,22.99,39.10,80.06,96.06,60.01,35.45,
     1  0.0,0.0/
C
C            NOPH  = 0: NO PRINTOUT FROM SUBROUTINE BPR
C                    1: FULL PRINTOUT
C                    2: SHORT FORM PRINTOUT
C
C            KI    = 1: INPUT CONCS IN PPM
C                    2: INPUT CONCS IN G-MOLE/LITER
C
C            JS    = 0: NO SOLIDS
C                  = 1: SOLIDS MAY BE PRESENT. PPCO2 SPECIFIED.
C
C            TK    =    SLURRY TEMPERATURE, DEGREES KELVIN
C
C            PP    =    PARTIAL PRESSURES OF SO2,CO2 IN ATM
C
C            SS(1) =    RELATIVE SATURATION OF CASO3 AT WHICH
C                       CRYSTALLIZATION OCCURS. USE VALUE OF 1.00
C                       FOR NORMAL RADIAN EQUILIBRIUM.
C
C            SS(3)      APPLIES TO CASO4
C
C            IPH   = 0: PH NOT SPECIFIED
C                    1: PH IS SPECIFIED
C
C            PH    =    SLURRY PH (FOR INPUT, SET = 0. IF NOT SPECIFIED)
C
C            CCM   =    INPUT DATA CONCS OF CA,MG,NA,K,SO3,SO4,CO3,CL
C                       IN THAT ORDER.
C
C            CM    =    CONCS OF SO3,CO3,SO4,NO3,CA,MG,(NA+K),CL
C                       IN THAT ORDER, GMOL/LITER
C
100   CONTINUE
C          READ A NEW CASE:  INPUT DATA FROM FILE "BEQ DATA".
      READ (5,110,END=200) IDENT
110   FORMAT( 20A4)
      CALL TIMES (ICPU, ITOD, HMS, DATE)
      WRITE (6,112) DATE, HMS
```

```
112    FORMAT( 1H1, 50X, A8, ' AT ', A5)
       WRITE (6,115) IDENT
115    FORMAT(1H , 5X, 20A4)
       READ (5,120,END=160) XPR, XK1, SJ, TK, PP(1), PP(2), SS(1),
      1 SS(3), XIPH, PH
       READ (5,120,END=160) (CCM(I),I=1,8)
120    FORMAT( 10G99.0)
       K1 = XK1
       NOPR = XPR
C            CHECK INPUT CONCNS:
       DO 3 I = 1,8
       IF (CCM(I).GE.0.) GO TO 3
       WRITE (6,170) CMP(I), CCM(I)
170    FORMAT( 1H0, 'INPUT ERROR: CONCN UF ',A8, ' IS NEGATIVE: ',F12.5/
      1 6X, 'SKIP TO NEXT CASE.')
       GO TO 100
3      CONTINUE
C            CALC CONCNS IN GMOL/L AND PPM:
       IF(K1.EQ.1) GO TO 20
       DO 10 I = 1,8
       CW(I) = 1000. * CCM(I) * XMW(I)
   10  CONTINUE
       GO TO 40
   20  CONTINUE
       DO 30 I = 1,8
       CW(I) = CCM(I)
       CCM(I) = 0.001 * CCM(I) / XMW(I)
30     CONTINUE
   40  CONTINUE
C            DO MODIFIED RADIAN CALC:
       EPS = .00000001
       JS = SJ
       IPH = XIPH
       PPSO2 = PP(1)
       PPCO2 = PP(2)
       SS1 = SS(1)
       SS3 =SS(3)
       KK1 = K1
       JJS = JS
       PPH = PH
       IF(TK.GT.273.) GO TO 45
       WRITE (6,175) TK
175    FORMAT( 1H0, 'INPUT TEMP OF ', F6.1, ' K IS TOO LUW FOR',
      1 ' RADIAN CALC:' / 6X, 'SKIP TO NEXT CALC.')
       GO TO 100
   45  CONTINUE
       CM(1) = CCM(5)
       CM(2) = CCM(7)
       CM(3) = CCM(6)
       CM(4) = 0.
       CM(5) = CCM(1)
       CM(6) = CCM(2)
       CM(7) = CCM(3)+CCM(4)
       CM(8) = CCM(8)
       EPSNA = 1.E-10
      IF(CM(7).GT.EPSNA) FNA = CCM(3)/CM(7)                             LCA01110
      IOPT = 0                                                          LCA01120
      IF(PP(2).GT.EPS) IOPT = 2                                         LCA01130
      IF(PP(1).GT.EPS) IOPT = IOPT+1                                    LCA01140
      CALL BEQ (NOPR,JS,IOPT,TK,X,CM,PP,SS,IPH,PH,FNA)                  LCA01150
      GO TO 100                                                         LCA01160
  160 CONTINUE                                                          LCA01170
      WRITE (6,180)                                                     LCA01180
180   FORMAT( 1H0, 'INPUT DATA INCOMPLETE FOR THIS CASE.')              LCA01190
200   CONTINUE                                                          LCA01200
      WRITE(6,210)                                                      LCA01210
210   FORMAT(1H0,'END OF DATA')                                         LCA01220
 1000 CONTINUE                                                          LCA01230
      STOP                                                              LCA01240
      END                                                               LCA01250
```

```
BEQ      FORTRAN  P     ID=BECCLI           12/19/74    10.57.59          PAGE 1
         VP/CSS   ---       NATIONAL CSS, INC. (SUNNYVALE DATA CENTER)

      SUBROUTINE BEQ (NOPR,JSS,IOPT,TK,X,CM,PP,SS,IPH,PH,FNA)           LIQ00010
C********************************************************************** LIQ00020
C****** THIS ROUTINE DETERMINES AQUEOUS SOLUTION EQUILIBRIA FOR THE      LIQ00030
C       SYSTEM SO2,CO2,SO3,N2O5,CA,MG,NA,CL.                             LIQ00040
C                                                                        LIQ00050
C****** FOR JSS=1 AND SPECIFIED PPCO2, SOLIDS ARE ALSO DETERMINED.       LIQ00060
C                                                                        LIQ00070
C********************************************************************** LIQ00080
C                                                                        LIQ00090
C                              COMPONENTS                                LIQ00100
C                                                                        LIQ00110
C                              (1)    H+                                 LIQ00120
C                              (2)    OH-                                LIQ00130
C                              (3)    H2CO3                              LIQ00140
C                              (4)    HCO3-                              LIQ00150
C                              (5)    CO3--                              LIQ00160
C                              (6)    H2SO3                              LIQ00170
C                              (7)    HSO3-                              LIQ00180
C                              (8)    SO3--                              LIQ00190
C                              (9)    HSO4-                              LIQ00200
C                              (10)   SO4--                              LIQ00210
C                              (11)   CA++                               LIQ00220
C                              (12)   CAOH+                              LIQ00230
C                              (13)   CAHCO3+                            LIQ00240
C                              (14)   CACO3                              LIQ00250
C                              (15)   CASO3                              LIQ00260
C                              (16)   CASO4                              LIQ00270
C                              (17)   MG++                               LIQ00280
C                              (18)   MGOH+                              LIQ00290
C                              (19)   MGHCO3+                            LIQ00300
C                              (20)   MGCO3                              LIQ00310
C                              (21)   MGSO3                              LIQ00320
C                              (22)   MGSO4                              LIQ00330
C                              (23)   NO3-                               LIQ00340
C                              (24)   CANO3+                             LIQ00350
C                              (25)   NA+                                LIQ00360
C                              (26)   NANO3                              LIQ00370
C                              (27)   NAOH                               LIQ00380
C                              (28)   NAHCO3                             LIQ00390
C                              (29)   NACO3-                             LIQ00400
C                              (30)   NASO4-                             LIQ00410
C                              (31)   CL-                                LIQ00420
C                              (32)   CACO3 (S)                          LIQ00430
C                              (33)   CASO3 (S)                          LIQ00440
C                              (34)   CASO4 (S)                          LIQ00450
C                              (35)   CA(OH)2 (S)                        LIQ00460
C                              (36)   MGCO3 (S)                          LIQ00470
C                              (37)   MG(OH)2 (S)                        LIQ00480
C                                                                        LIQ00490
C                                                                        LIQ00500
C                                                                        LIQ00510
C                                                                        LIQ00520
C                                                                        LIQ00530
C                                                                        LIQ00540
C                                                                        LIQ00550
```

```
C                                                                       LIQ00560
C         EQUATIONS                                                     LIQ00570
C                                                                       LIQ00580
C         (1)   (H+)(OH-) = K(1)                                        LIQ00590
C                                                                       LIQ00600
C         (2)   (H2CO3) = PPCO2/K(2)                                    LIQ00610
C                                                                       LIQ00620
C         (3)   (H+)(HCO3-) = (H2CO3)*K(3)                              LIQ00630
C                                                                       LIQ00640
C         (4)   (H+)(CO3--) = (HCO3-)*K(4)                              LIQ00650
C                                                                       LIQ00660
C         (5)   (H+)(HSO3-) = (H2SO3)*K(5)                              LIQ00670
C                                                                       LIQ00680
C         (6)   (H+)(SO3--) = (HSO3-)*K(6)                              LIQ00690
C                                                                       LIQ00700
C         (7)   (H+)(SO4--) = (HSO4-)*K(7)                              LIQ00710
C                                                                       LIQ00720
C         (8)   (CA++)(OH-) = (CAOH+)*K(8)                              LIQ00730
C                                                                       LIQ00740
C         (9)   (CA++)(HCO3-) = (CAHCO3+)*K(9)                          LIQ00750
C                                                                       LIQ00760
C         (10)  (CA++)(CO3--) = (CACO3)*K(10)                           LIQ00770
C                                                                       LIQ00780
C         (11)  (CA++)(SO3--) = (CASO3)*K(11)                           LIQ00790
C                                                                       LIQ00800
C         (12)  (CA++)(SO4--) = (CASO4)*K(12)                           LIQ00810
C                                                                       LIQ00820
C         (13)  (MG++)(OH-) = (MGOH+)*K(13)                             LIQ00830
C                                                                       LIQ00840
C         (14)  (MG++)(HCO3-) = (MGHCO3+)*K(14)                         LIQ00850
C                                                                       LIQ00860
C         (15)  (MG++)(CO3--) = (MGCO3)*K(15)                           LIQ00870
C                                                                       LIQ00880
C         (16)  (MG++)(SO3--) = (MGSO3)*K(16)                           LIQ00890
C                                                                       LIQ00900
C         (17)  (MG++)(SO4--) = (MGSO4)*K(17)                           LIQ00910
C                                                                       LIQ00920
C         (18)  SO2 MATERIAL BALANCE                                    LIQ00930
C                                                                       LIQ00940
C         (19)  SO3 MATERIAL BALANCE                                    LIQ00950
C                                                                       LIQ00960
C         (20)  CA MATERIAL BALANCE                                     LIQ00970
C                                                                       LIQ00980
C         (21)  MG MATERIAL BALANCE                                     LIQ00990
C                                                                       LIQ01000
C         (22)  CHARGE BALANCE                                          LIQ01010
C                                                                       LIQ01020
C         (23)  (H2SO3) = PPSO2/K(23)                                   LIQ01030
C                                                                       LIQ01040
C         (24)  (CA++)(NO3-) = (CANO3+)*K(24)                           LIQ01050
C                                                                       LIQ01060
C         (25)  (NA+)(NO3-) = (NANO3)*K(25)                             LIQ01070
C                                                                       LIQ01080
C         (26)  (NA+)(OH-) = (NAOH)*K(26)                               LIQ01090
C                                                                       LIQ01100
```

```
C              (27)  (NA+)(HCO3-) = (NAHCO3)*K(27)                          LIQ01110
C                                                                           LIQ01120
C              (28)  (NA+)(CO3--) = (NACO3-)*K(28)                          LIQ01130
C                                                                           LIQ01140
C              (29)  (NA+)(SO4--) = (NASO4-)*K(29)                          LIQ01150
C                                                                           LIQ01160
C              (30)  CO2 MATERIAL BALANCE                                   LIQ01170
C                                                                           LIQ01180
C              (31)  NO2 MATERIAL BALANCE                                   LIQ01190
C                                                                           LIQ01200
C              (32)  NA MATERIAL BALANCE                                    LIQ01210
C                                                                           LIQ01220
C              (33)  (CL-) = CONSTANT                                       LIQ01230
C                                                                           LIQ01240
C              (34)  (CA++)(CO3--) L.E. K(34)                               LIQ01250
C                                                                           LIQ01260
C              (35)  (CA++)(SO3--) L.E. K(35)                               LIQ01270
C                                                                           LIQ01280
C              (36)  (CA++)(SO4--) L.E. K(36)                               LIQ01290
C                                                                           LIQ01300
C              (37)  (CA++)(OH-)**2 L.E. K(37)                              LIQ01310
C                                                                           LIQ01320
C              (38)  (MG++)(CO3--) L.E. K(38)                               LIQ01330
C                                                                           LIQ01340
C              (39)  (MG++)(OH-)**2 L.E. K(39)                              LIQ01350
C                                                                           LIQ01360
C                                                                           LIQ01370
C                                                                           LIQ01380
C                                                                           LIQ01390
C                                                                           LIQ01400
C                                                                           LIQ01410
C                                                                           LIQ01420
C                                                                           LIQ01430
C                                                                           LIQ01440
C                                                                           LIQ01450
C                                                                           LIQ01460
C                                                                           LIQ01470
C                                                                           LIQ01480
C                                                                           LIQ01490
C                                                                           LIQ01500
C                                                                           LIQ01510
C                                                                           LIQ01520
C                                                                           LIQ01530
C                                                                           LIQ01540
C                                                                           LIQ01550
C                                                                           LIQ01560
C                                                                           LIQ01570
C                                                                           LIQ01580
C                                                                           LIQ01590
C                                                                           LIQ01600
C                                                                           LIQ01610
C                                                                           LIQ01620
C                                                                           LIQ01630
C                                                                           LIQ01640
C                                                                           LIQ01650
```

```
C
      DIMENSION X(50),CM(10),PP(2),IFLAG(10),SS(3)
      COMMON/CEE/C1,C3,C5,C6,C7,F1,F3
      COMMON/GAMMA/GAM(50)
      COMMON/TEMP/AC,BC,CPK(2),CK(50)
      COMMON/COMP/LON
      COMMON/PRESS/PP1,PP2
      REAL K(50),LOW
      JS = JSS
    2 CONTINUE
      X(1) = 0.
      EPS = .00000001
      IF(JS.NE.JSS) PP(1) = PP1
      PP1 = PP(1)
      PP2 = PP(2)
      LON = 0
      SCASO3 = 1000.
      CM15 = CM(1)-CM(5)
      CM35 = CM(3)-CM(5)
      IF(IOPT.EQ.3.OR.IOPT.EQ.1) CM(1) = 0.
      IF(IOPT.EQ.2.OR.IOPT.EQ.3) CM(2) = 0.
      IF(CM(4).GT.EPS.OR.CM(7).GT.EPS.OR.CM(8).GT.EPS) LON = 1
      IT = 5
      TOL = 0.01
      IF(JS.NE.0) TOL = 0.0001
      IF(IPH.EQ.1) GO TO 5
      ACID = CM(1)+CM(3)+0.5*CM(4)+0.5*CM(8)-CM(5)-CM(6)-0.5*CM(7)
      IF(ACID.LE.0.) X(1) = 1.E-6
      IF(ACID.GT.0.) X(1) = 1.E-4
      IF(LON.EQ.1.AND.CM(7).GT.(CM(5)+CM(6)).AND.ACID.LT.0.) X(1) =
     1 1.E-8
      IF(PP(1).GT..0001) X(1) = 1.E-4
    5 CONTINUE
      IF(JS.NE.JSS) GO TO 30
      KOUNT = 0
      KN = 0
      KP = 0
      DO 10 I=1,7
      IFLAG(I) = 0
      IF(CM(I).LT.EPS) GO TO 10
      IFLAG(I) = 1
      KOUNT = KOUNT+1
      IF(I.GT.4) KP = KP+1
      IF(I.LT.5) KN = KN+1
   10 CONTINUE
      IF(KP.EQ.0.OR.KN.EQ.0) IT = 1
      ISS = 1
      IF(JS.EQ.0.OR.IFLAG(5).EQ.0) ISS = 0
C****** CALCULATE TEMPERATURE-DEPENDENT CONSTANTS
      CALL TCON(JS,TK)
C
C****** INITIAL ESTIMATES FOR CONCENTRATIONS TO DETERMINE
C       ACTIVITY COEFFICIENTS
   30 CONTINUE
      DO 40 I=2,37
      X(I) = 0.                                                         LIQ02210
   40 CONTINUE                                                          LIQ02220
      X(7) = CM(1)                                                      LIQ02230
      X(10) = CM(3)                                                     LIQ02240
      X(11) = CM(5)                                                     LIQ02250
      X(17) = CM(6)                                                     LIQ02260
      X(23) = CM(4)                                                     LIQ02270
      X(25) = CM(7)                                                     LIQ02280
      X(31) = CM(8)                                                     LIQ02290
C****** OUTER LOOP FOR CONVERGENCE OF ACTIVITY COEFFICIENTS              LIQ02300
      ITGAM = 2                                                         LIQ02310
      IF(JS.NE.0) ITGAM = 3                                             LIQ02320
      DO 1000 JJ=1,ITGAM                                                LIQ02330
      ITC = 0                                                           LIQ02340
      HI = 20.                                                          LIQ02350
      LOW = -1.                                                         LIQ02360
      CALL KCALC(JJ,JS,X,SS,K)                                          LIQ02370
      IF(IPH.EQ.0) PH = -ALOG10(X(1)*GAM(1))                            LIQ02380
      IF(IPH.EQ.1) X(1) = 1./GAM(1)/(10.**PH)                           LIQ02390
      IF(IFLAG(2).EQ.0) X(3) = PP(2)/K(2)                               LIQ02400
      IF(IFLAG(1).EQ.0) X(6) = PP(1)/K(23)                              LIQ02410
C****** INNER LOOP FOR CONVERGENCE OF PH                                 LIQ02420
  100 CONTINUE                                                          LIQ02430
      X(2) = K(1)/X(1)                                                  LIQ02440
      IF(IFLAG(1).EQ.1) GO TO 102                                       LIQ02450
      X(7) = K(5)*X(6)/X(1)                                             LIQ02460
      X(8) = K(6)*X(7)/X(1)                                             LIQ02470
      GO TO 105                                                         LIQ02480
  102 CONTINUE                                                          LIQ02490
      X7X8 = X(1)/K(6)                                                  LIQ02500
      X6X8 = X7X8*X(1)/K(5)                                             LIQ02510
      C1 = 1.+X7X8+X6X8                                                 LIQ02520
  105 CONTINUE                                                          LIQ02530
      IF(IFLAG(2).EQ.1) GO TO 110                                       LIQ02540
      X(4) = K(3)*X(3)/X(1)                                             LIQ02550
      X(5) = K(4)*X(4)/X(1)                                             LIQ02560
      GO TO 115                                                         LIQ02570
  110 CONTINUE                                                          LIQ02580
      X4X5 = X(1)/K(4)                                                  LIQ02590
      X3X5 = X(1)*X(1)/K(4)/K(3)                                        LIQ02600
      C2 = 1.+X4X5+X3X5                                                 LIQ02610
  115 CONTINUE                                                          LIQ02620
      IF(IFLAG(3).EQ.0) GO TO 120                                       LIQ02630
      X9X10 = X(1)/K(7)                                                 LIQ02640
      C3 = 1.+X9X10                                                     LIQ02650
  120 CONTINUE                                                          LIQ02660
      IF(IFLAG(5).EQ.1) GO TO 130                                       LIQ02670
      X12X11 = X(2)/K(8)                                                LIQ02680
      IF(IFLAG(2).EQ.1) GO TO 125                                       LIQ02690
      X13X11 = X(4)/K(9)                                                LIQ02700
      X14X11 = X(5)/K(10)                                               LIQ02710
      C5 = 1.+X12X11+X13X11+X14X11                                      LIQ02720
      GO TO 130                                                         LIQ02730
  125 CONTINUE                                                          LIQ02740
      C5 = 1.+X12X11                                                    LIQ02750
  130 CONTINUE
      IF(IFLAG(6).EQ.0) GO TO 140
      X18X17 = X(2)/K(13)
      IF(IFLAG(2).EQ.1) GO TO 135
      X19X17 = X(4)/K(14)
      X20X17 = X(5)/K(15)
      C6 = 1.+X18X17+X19X17+X20X17
      GO TO 140
  135 CONTINUE
      C6 = 1.+X18X17
  140 CONTINUE
      IF(IFLAG(7).EQ.0) GO TO 150
      X27X25 = X(2)/K(26)
      IF(IFLAG(2).EQ.1) GO TO 145
      X28X25 = X(4)/K(27)
      X29X25 = X(5)/K(28)
      C7 = 1.+X27X25+X28X25+X29X25
      GO TO 150
  145 CONTINUE
      C7 = 1.+X27X25
  150 CONTINUE
      IF(JS.EQ.0) GO TO 195
      IF(IFLAG(5).EQ.0.OR.JS.GE.2) GO TO 180
      SCAOH2 = K(37)/X(2)/X(2)
      SCACO3 = K(34)/X(5)
      IF(PP(1).GT.1.E-20) SCASO3 = K(35)/X(8)
      IF(SCACO3.LT.SCASO3.AND.SCACO3.LT.SCAOH2) GO TO 160
      IF(SCAOH2.LT.SCASO3) GO TO 170
      SOL5 = SCASO3
      ISOL5 = 1
      GO TO 180
  160 CONTINUE
      SOL5 = SCACO3
      ISOL5 = 2
      GO TO 180
  170 CONTINUE
      SOL5 = SCAOH2
      ISOL5 = 3
  180 CONTINUE
      IF(IFLAG(6).EQ.0) GO TO 195
      SMGOH2 = K(39)/X(2)/X(2)
      SMGCO3 = K(38)/X(5)
      IF(SMGOH2.LT.SMGCO3) GO TO 190
      SOL6 = SMGCO3
      ISOL6 = 2
      GO TO 195
  190 CONTINUE
      SOL6 = SMGOH2
      ISOL6 = 3
  195 CONTINUE
      IF(JS.LT.2) GO TO 199
      IF(JS.EQ.3) GO TO 196
      IF(JS.EQ.4) GO TO 197
      CALL CASO3 (IFLAG,K,X,CM,PP,SOL6)
      GO TO 300
  196 CONTINUE                                                          LIQ03310
      CALL CASO4 (IFLAG,K,X,CM,PP,SOL6)                                 LIQ03320
      GO TO 300                                                         LIQ03330
  197 CONTINUE                                                          LIQ03340
      CALL CASOX (IFLAG,K,X,CM,PP,SOL6)                                 LIQ03350
      GO TO 300                                                         LIQ03360
  199 CONTINUE                                                          LIQ03370
C****** CALCULATE BASE IONS (SO3--,CO3--,SO4--,NO3-,CA++,MG++,NA+)      LIQ03380
      IF(IFLAG(1).EQ.1) X(8) = 0.                                       LIQ03390
      IF(IFLAG(2).EQ.1) X(5) = 0.                                       LIQ03400
      X(10) = 0.                                                        LIQ03410
      X(23) = 0.                                                        LIQ03420
      FS1 = 0.                                                          LIQ03430
      FS3 = 0.                                                          LIQ03440
      C5S = C5                                                          LIQ03450
      C6S = C6                                                          LIQ03460
      C7S = C7                                                          LIQ03470
      DO 255 I=1,IT                                                     LIQ03480
      IF(IFLAG(2).EQ.0) GO TO 200                                       LIQ03490
      X514 = X(5)*X4X5                                                  LIQ03500
      IF(IFLAG(5).EQ.1) C5 = C5S+X(5)/K(10)+X514/K(9)                   LIQ03510
      IF(IFLAG(6).EQ.1) C6 = C6S+X(5)/K(15)+X514/K(14)                  LIQ03520
      IF(IFLAG(7).EQ.1) C7 = C7S+X(5)/K(28)+X514/K(27)                  LIQ03530
  200 CONTINUE                                                          LIQ03540
      IF(IFLAG(5).EQ.0) GO TO 210                                       LIQ03550
      X(11) = CM(5)/(C5+X(8)/K(11)+X(10)/K(12)+X(23)/K(24)+FS1+FS3)     LIQ03560
      IF(JS.NE.0) X(11) = AMIN1(X(11),SOL5)                             LIQ03570
  210 CONTINUE                                                          LIQ03580
      IF(IFLAG(6).EQ.0) GO TO 220                                       LIQ03590
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))                         LIQ03600
      IF(JS.NE.0) X(17) = AMIN1(X(17),SOL6)                             LIQ03610
  220 CONTINUE                                                          LIQ03620
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))      LIQ03630
      IF(IFLAG(1).EQ.0) GO TO 230                                       LIQ03640
      F1 = C1+X(11)/K(11)+X(17)/K(16)                                   LIQ03650
      X(8) = CM(1)/F1                                                   LIQ03660
      IF (IS5.EQ.0) GO TO 230                                           LIQ03670
      X(8) = AMIN1(X(8),K(35)/X(11))                                    LIQ03680
      X(8) = AMAX1(X(8),CM15/F1)                                        LIQ03690
      FS1 = X(8)*(CM(1)-X(8)*F1)/K(35)                                  LIQ03700
  230 CONTINUE                                                          LIQ03710
      IF(IFLAG(2).EQ.1) X(5) = CM(2)/(C2+X(11)/K(10)+X(11)*X4X5/K(9)    LIQ03720
     1 +X(17)/K(15)+X(17)*X4X5/K(14)+X(25)/K(28)+X(25)*X4X5/K(27))      LIQ03730
      IF(IFLAG(3).EQ.0) GO TO 240                                       LIQ03740
      F3 = C3+X(11)/K(12)+X(17)/K(17)+X(25)/K(29)                       LIQ03750
      X(10) = CM(3)/F3                                                  LIQ03760
      IF(IS5.EQ.0) GO TO 240                                            LIQ03770
      X(10) = AMIN1(X(10),K(36)/X(11))                                  LIQ03780
      X(10) = AMAX1(X(10),CM35/F3)                                      LIQ03790
      FS3 = X(10)*(CM(3)-X(10)*F3)/K(36)                                LIQ03800
  240 CONTINUE                                                          LIQ03810
      IF(IFLAG(4).EQ.1) X(23) = CM(4)/(1.+X(11)/K(24)+X(25)/K(25))      LIQ03820
  255 CONTINUE                                                          LIQ03830
  256 CONTINUE                                                          LIQ03840
C****** CALCULATE ALL UNDETERMINED IONS                                 LIQ03850
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  300 CONTINUE
      IF(IFLAG(1).EQ.0) GO TO 310
      X(7) = X(8)*X7X8
  310 CONTINUE
      IF(IFLAG(2).EQ.0) GO TO 315
      X(4) = X(5)*X4X5
  315 CONTINUE
      IF(IFLAG(3).EQ.0) GO TO 320
      X(9) = X(10)*X9X10
  320 CONTINUE
      IF(IFLAG(5).EQ.0) GO TO 330
      X(12) = X(11)*X12X11
      X(24) = X(11)*X(23)/K(24)
      X(13) = X(11)*X(4)/K(9)
  330 CONTINUE
      IF(IFLAG(6).EQ.0) GO TO 340
      X(18) = X(17)*X18X17
      X(19) = X(17)*X(4)/K(14)
  340 CONTINUE
      IF(IFLAG(7).EQ.0) GO TO 342
      X(29) = X(25)*X(5)/K(28)
      X(30) = X(25)*X(10)/K(29)
  342 CONTINUE
      IF(IPH.EQ.1) GO TO 500
C****** CALCULATE NEW VALUE OF (H+)
      PHIS = PHI
      PHI = 2.*(X(17)+X(11)-X(5)-X(8)-X(10))+X(1)+X(12)+X(13)+X(18)
     1 +X(19)+X(24)+X(25)-X(2)-X(4)-X(7)-X(9)-X(23)-X(29)-X(30)-X(31)
      ITO = ITO+1
      IF(JJ.GT.1.AND.ITO.EQ.1.AND.ABS(PHI).LT.2.*ABS(PHIS)) GO TO 500
      IF(PHI.LT.0.) GO TO 360
      LOW = PH
      IF(HI.LT.14.) GO TO 350
      PH = PH+1.
      X(1) = X(1)/10.
      GO TO 100
  350 CONTINUE
      IF((HI-LOW).LT.TOL) GO TO 500
      PH = (HI+LOW)/2.
      X(1) = 1./GAM(1)/(10.**PH)
      GO TO 100
  360 CONTINUE
      HI = PH
      IF(LOW.GT.0.) GO TO 350
      PH = PH-1.
      X(1) = X(1)*10.
      GO TO 100
  500 CONTINUE
 1000 CONTINUE
C****** ITERATIVE CALCULATION COMPLETE
C
C****** CALCULATE NEUTRAL MOLECULES
      IF(IFLAG(1).EQ.0) GO TO 520
      X(6) =    X(8)*X6X8
      PP(1) = X(6)*K(23)
  520 CONTINUE
      IF(IFLAG(2).EQ.0) GO TO 540                                       LIQ04410
      X(3) = X(5)*X3X5                                                  LIQ04420
      PP(2) = X(3)*K(2)                                                 LIQ04430
  540 CONTINUE                                                          LIQ04440
      X(14) = X(11)*X(5)/K(10)                                          LIQ04450
      X(15) = X(11)*X(8)/K(11)                                          LIQ04460
      X(16) = X(11)*X(10)/K(12)                                         LIQ04470
      X(20) = X(17)*X(5)/K(15)                                          LIQ04480
      X(21) = X(17)*X(8)/K(16)                                          LIQ04490
      X(22) = X(17)*X(10)/K(17)                                         LIQ04500
      X(26) = X(25)*X(23)/K(25)                                         LIQ04510
      X(27) = X(25)*X27X25                                              LIQ04520
      X(28) = X(25)*X(4)/K(27)                                          LIQ04530
      IF(JS.EQ.0) GO TO 1010                                            LIQ04540
C****** CALCULATE SOLIDS                                                LIQ04550
      EPS1 = 1.E-6                                                      LIQ04560
      IF(IFLAG(5).EQ.0) GO TO 1001                                      LIQ04570
      IF(JS.EQ.3) GO TO 600                                             LIQ04580
      IF(IFLAG(1).EQ.1) X(33) = CM(1)-X(8)*F1                           LIQ04590
      IF(JS.EQ.2) GO TO 1001                                            LIQ04600
  600 CONTINUE                                                          LIQ04610
      IF(IFLAG(3).EQ.1) X(34) = CM(3)-X(10)*F3                          LIQ04620
      IF(JS.NE.1) GO TO 1001                                            LIQ04630
      F5 = C5+X(8)/K(11)+X(10)/K(12)+X(23)/K(24)                        LIQ04640
      IF(ISOL5.EQ.1) X(33) = CM(5)-X(34)-X(11)*F5                       LIQ04650
      IF(ISOL5.EQ.2) X(32) = CM(5)-X(33)-X(34)-X(11)*F5                 LIQ04660
      IF(ISOL5.EQ.3) X(35) = CM(5)-X(33)-X(34)-X(11)*F5                 LIQ04670
      IF(X(32).GT.EPS1.OR.X(35).GT.EPS1) GO TO 1001                     LIQ04680
      IF(X(33).GT.EPS1) GO TO 650                                       LIQ04690
      IF(X(34).LT.EPS1) GO TO 1001                                      LIQ04700
      JS = 3                                                            LIQ04710
      GO TO 2                                                           LIQ04720
  650 CONTINUE                                                          LIQ04730
      IF(ISOL5.EQ.1) GO TO 1001                                         LIQ04740
      IF(X(34).LT.EPS1) JS=2                                            LIQ04750
      IF(X(34).GT.EPS1) JS=4                                            LIQ04760
      GO TO 2                                                           LIQ04770
 1001 CONTINUE                                                          LIQ04780
      IF(IFLAG(6).EQ.0) GO TO 1002                                      LIQ04790
      F6 = C6+X(8)/K(16)+X(10)/K(17)                                    LIQ04800
      IF(ISOL6.EQ.2) X(36) = CM(6)-X(17)*F6                             LIQ04810
      IF(ISOL6.EQ.3) X(37) = CM(6)-X(17)*F6                             LIQ04820
 1002 CONTINUE                                                          LIQ04830
      DO 1005 I=32,37                                                   LIQ04840
      IF(X(I).LT.EPS1) X(I) = 0.                                        LIQ04850
 1005 CONTINUE                                                          LIQ04860
 1010 CONTINUE                                                          LIQ04870
      SS(1) = X(8) * X(11) / K(35)                                      LIQ04880
      SS(3) = X(10) * X(11) / K(36)                                     LIQ04890
C****** WRITE OUTPUT                                                    LIQ04900
      IP = NOPR                                                         LIQ04910
      IF(IP.NE.0)CALL BEOPRT(NOPR,IOPT,IFLAG,TK,X,CM,PP,SS,IPH,PH,FNA)  LIQ04920
      RETURN                                                            LIQ04930
      END                                                               LIQ04940
                                                                        LIQ04950
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BEQCON   FORTRAN  P      ID=HECCL1           12/19/74    10.58.32         PAGE 1
       VP/CSS    ---       NATIONAL CSS, INC. (SUNNYVALE DATA CENTER)

      SUBROUTINE KCALC (JJ,JS,X,SS,K)
C***********************************************************************
C****** THIS ROUTINE DETERMINES ACTIVITY COEFFICIENTS, GAM, AND
C       EQUILIBRIUM CONSTANTS, K, FOR THE SO2,CO2,SO3,N2O5,CA,MG,NA,CL
C       SYSTEM.
C***********************************************************************
      COMMON/TEMP/AC,BC,CPK(2),CK(50)
      COMMON/GAMMA/GAM(50)
      COMMON/COMP/LON
      DIMENSION A(11),B(11),C(31),CC(11),U(11),SS(3)
      REAL K(50),X(50)
      DATA  A/6.,3.,3.,4.5,4.5,3.,4.5,3.,2.,5.,4./
      DATA  B/.4,.3,.3,0.,0.,0.,.1,.3,-.2,.1,0./
      DATA  C/1.,1.,0.,1.,4.,0.,1.,4.,1.,4.,4.,1.,1.,0.,0.,0.,
     1 4.,1.,1.,0.,0.,0.,1.,1.,1.,0.,0.,0.,1.,1.,1./
      DATA  CC/1.,1.,0.,1.,4.,4.,4.,4.,1.,1.,1./
      DATA  U/0.,0.,.076,0.,0.,0.,0.,0.,0.,0.,0./
      GAM(12) = 1.
      IF(JS.NE.0.AND.JJ.EQ.1) GO TO 42
      FI = 0.
      DO 20 I=1,31
      FI = FI+X(I)*C(I)
   20 CONTINUE
      FI = FI/2.
      SFI = SQRT(FI)
      IT2 = 11
      IF(LON.EQ.0) IT2 = 8
      DO 40 I=1,IT2
      DNM = 1.+BC*A(I)*SFI
      ACF = AC*CC(I)
      UM = 2.3026*U(I)
      GAM(I) = EXP(ACF*(-SFI/DNM+B(I)*FI)+UM*FI)
   40 CONTINUE
      GO TO 50
   42 CONTINUE
      GAM(1) = 0.8
      GAM(2) = 0.8
      GAM(3) = 1.
      GAM(4) = 0.8
      GAM(5) = 0.4
      GAM(6) = 0.4
      GAM(7) = 0.4
      GAM(8) = 0.4
      GAM(9) = 0.8
      GAM(10) = 0.8
      GAM(11) = 0.8
   50 CONTINUE
      K(1) = CK(1)/(GAM(1)*GAM(2))
      K(2) = GAM(3)/CPK(2)
      G314 = GAM(3)/(GAM(1)*GAM(4))
      K(3) = CK(3)*G314
      G415 = GAM(4)/(GAM(1)*GAM(5))
      K(4) = CK(4)*G415
      K(5) = CK(5)*G314
      K(6) = CK(6)*G415
      K(7) = CK(7)*GAM(2)/(GAM(1)*GAM(6))                              KC200560
      K(8) = CK(8)/GAM(7)                                              KC200570
      K(9) = CK(9)*GAM(2)/(GAM(7)*GAM(4))                              KC200580
      G375 = GAM(3)/(GAM(7)*GAM(5))                                    KC200590
      K(10) = CK(10)*G375                                              KC200600
      K(11) = CK(11)*G375                                              KC200610
      G76 = GAM(7)*GAM(6)                                              KC200620
      K(12) = CK(12)*GAM(3)/G76                                        KC200630
      K(13) = CK(13)/GAM(8)                                            KC200640
      K(14) = CK(14)*GAM(2)/(GAM(8)*GAM(4))                            KC200650
      G385 = GAM(3)/(GAM(8)*GAM(5))                                    KC200660
      K(15) = CK(15)*G385                                              KC200670
      K(16) = CK(16)*G385                                              KC200680
      K(17) = CK(17)*GAM(3)/(GAM(8)*GAM(6))                            KC200690
      K(23) = GAM(3)/CPK(1)                                            KC200700
      IF(LON.EQ.1) GO TO 60                                            KC200710
      DO 45 I=24,29                                                    KC200720
      K(I) = 1.                                                        KC200730
   45 CONTINUE                                                         KC200740
      GO TO 70                                                         KC200750
   60 CONTINUE                                                         KC200760
      K(24) = CK(18)*GAM(2)/(GAM(7)*GAM(9))                            KC200770
      K(25) = CK(19)*GAM(3)/(GAM(10)*GAM(9))                           KC200780
      K(26) = CK(20)*GAM(3)/(GAM(2)*GAM(10))                           KC200790
      K(27) = CK(21)*GAM(3)/(GAM(4)*GAM(10))                           KC200800
      K(28) = CK(22)*GAM(2)/(GAM(5)*GAM(10))                           KC200810
      K(29) = CK(23)*GAM(2)/(GAM(6)*GAM(10))                           KC200820
   70 CONTINUE                                                         KC200830
      G75 = GAM(7)*GAM(5)                                              KC200840
      K(34) = CK(24)/G75                                               KC200850
      K(35) = CK(25)*SS(1)/G75                                         KC200860
      K(36) = CK(26)*SS(3)/G76                                         KC200870
      G22 = 1./(GAM(2)*GAM(2))                                         KC200880
      K(37) = CK(27)*G22/GAM(7)                                        KC200890
      K(38) = CK(28)/(GAM(8)*GAM(5))                                   KC200900
      K(39) = CK(29)*G22/GAM(8)                                        KC200910
      RETURN                                                           KC200920
      END                                                              KC200930
C                                                                      KC200940
C                                                                      KC200950
C                                                                      KC200960
C                                                                      KC200970
C                                                                      KC200980
C                                                                      KC200990
C                                                                      KC201000
C                                                                      KC201010
C                                                                      KC201020
C                                                                      KC201030
C                                                                      KC201040
C                                                                      KC201050
C                                                                      KC201060
C                                                                      KC201070
C                                                                      KC201080
C                                                                      KC201090
C                                                                      KC201100
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      SUBROUTINE TCON(JS,TK)                                            KC201110
C****** TEMPERATURE-DEPENDENT CONSTANTS ARE DETERMINED HERE.            KC201120
      COMMON/COMP/LON                                                   KC201130
      COMMON/TEMP/AC,BC,CPK(2),CK(50)                                   KC201140
      DIMENSION A(29),B(29),C(29),D(29)                                 KC201150
C                                                                       KC201160
      DATA  A/4470.99,0.,3404.71,2902.39,-843.67,-633.84,475.14,        KC201170
     1 -273.,-301.85,-475.48,-504.8,2572.1,-517.99,-235.08,-504.8,      KC201180
     2 -432.5,-1057.86,-1245.,0.,0.,0.,-303.41,-241.,-1660.,0.,4944.0,  KC201190
     3 530.49,-955.14,-480.85/                                          KC201200
C                                                                       KC201210
      DATA  B/0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,23.15,0.,0.,0.,0.,0.,    KC201220
     1 0.,0.,0.,0.,0.,0.,0.,0.,37.745,-12.9722,0.,0./                   KC201230
C                                                                       KC201240
      DATA  C/.01706,0.,.032786,.02379,0.,0.,.018222,0.,0.,0.,0.,       KC201250
     1 0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,.032331,0.,0.       KC201260
     2/                                                                 KC201270
C                                                                       KC201280
      DATA  D/6.0875,0.,14.8435,6.4980,-4.7171,-9.3320,5.0435,-2.29,    KC201290
     1 -2.272,-4.7954,-5.091,63.60,-4.3223,-1.747,-5.091,-4.3715,-5.7950KC201300
     2 ,-4.49,.40,.57,.25,-2.2852,-1.529,-13.88,-6.347,105.36,-25.7085, KC201310
     3 -7.871,-12.514/                                                  KC201320
C                                                                       KC201330
      EPS = .000001                                                     KC201340
      IF(JS.EQ.JSOLD.AND.LON.EQ.LONOLD.AND.ABS(TK-TOLD).LT.EPS) RETURN  KC201350
      TC = TK-273.16                                                    KC201360
      TC2 = TC*TC                                                       KC201370
      DC = 87.740-0.40008*TC+9.398E-4*TC2-1.410E-6*TC2*TC               KC201380
      DCTK = DC*TK                                                      KC201390
      SQDCTK = SQRT(DCTK)                                               KC201400
      AC = 1.8246E6*2.3026/(DCTK*SQDCTK)                                KC201410
      BC = 50.29/SQDCTK                                                 KC201420
      DM = 2.3025851                                                    KC201430
      TLOG = ALOG10(TK)                                                 KC201440
      DO 10 I=1,29                                                      KC201450
      CK(I) = EXP(DM*(-A(I)/TK-B(I)*TLOG-C(I)*TK+D(I)))                 KC201460
   10 CONTINUE                                                          KC201470
CC*   IF(JS.NE.1.AND.TC.GT.40.) CK(26) = EXP(DM*(-1200.9/TK+6.6489*TLOG-KC201480
CC*  1 0.032057*TK-7.084))                                              KC201490
      CPK(1) = EXP(DM*(1370./TK-4.51))                                  KC201500
      CPK(2) = EXP(DM*(1015./TK-4.87))                                  KC201510
      TOLD = TK                                                         KC201520
      JSOLD = JS                                                        KC201530
      LONOLD = LON                                                      KC201540
      RETURN                                                            KC201550
      END                                                               KC201560
```

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BEQSOX   FORTRAN  P      ID=HECCL1             12/19/74    10.58.42          PAGE 1
     VP/CSS     ---       NATIONAL CSS, INC. (SUNNYVALE DATA CENTER)

      SUBROUTINE CAS03(IFLAG,K,X,CM,PP,SOL6)
      DIMENSION X(50),CM(10),PP(2),IFLAG(10)
      COMMON/CEE/C1,C3,C5,C6,C7,F1,F3
      REAL K(50)
      IT = 5
      IF(IFLAG(3).EQ.0.AND.IFLAG(4).EQ.0.AND.IFLAG(6).EQ.0
     1 .AND.IFLAG(7).EQ.0) IT = 1
      CM15 = ABS(CM(1)-CM(5))
      CM15SQ = CM15*CM15
      IF(CM(5).GT.CM(1)) GO TO 200
      X(11) = 0.
      X(17) = 0.
      X(25) = 0.
      DO 100 I=1,IT
      IF(IFLAG(3).EQ.1) X(10) = CM(3)/(C3+X(11)/K(12)+X(17)/K(17)
     1 +X(25)/K(29))
      IF(IFLAG(4).EQ.1) X(23) = CM(4)/(1.+X(11)/K(24)+X(25)/K(25))
      F1 = C1+X(17)/K(16)
      F5 = C5+X(10)/K(12)+X(23)/K(24)
      DISC = CM15SQ+4.*K(35)*F5*F1
      X(8) = (CM15+SQRT(DISC))/(2.*F1)
      X(11) = K(35)/X(8)
      IF(IFLAG(6).EQ.0) GO TO 50
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))
      X(17) = AMIN1(X(17),SOL6)
   50 CONTINUE
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))
  100 CONTINUE
      F1 = C1+X(11)/K(11)+X(17)/K(16)
      RETURN
  200 CONTINUE
      X(8) = 0.
      X(10) = 0.
      X(23) = 0.
      DO 250 I=1,IT
      IF(IFLAG(6).EQ.0) GO TO 230
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))
      X(17) = AMIN1(X(17),SOL6)
  230 CONTINUE
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))
      F1 = C1+X(17)/K(16)
      F5 = C5+X(10)/K(12)+X(23)/K(24)
      DISC = CM15SQ+4.*K(35)*F5*F1
      X(11) = (CM15+SQRT(DISC))/(2.*F5)
      X(8) = K(35)/X(11)
      IF(IFLAG(3).EQ.1) X(10) = CM(3)/(C3+X(11)/K(12)+X(17)/K(17)
     1 +X(25)/K(25))
  250 CONTINUE
      F1 = C1+X(11)/K(11)+X(17)/K(16)
      RETURN
      END
C
C
C
C
```

```
      SUBROUTINE CASO4 (IFLAG,K,X,CM,PP,SOL6)                           CS200560
      DIMENSION X(50),CM(10),PP(2),IFLAG(10)                            CS200570
      COMMON/CEF/C1,C3,C5,C6,C7,F1,F3                                   CS200580
      REAL K(50)                                                        CS200590
      IT = 5                                                            CS200600
      IF(IFLAG(1).EQ.0.AND.IFLAG(4).EQ.0.AND.IFLAG(6).EQ.0.AND.IFLAG(7) CS200610
     1.EQ.0) IT = 1                                                     CS200620
      CM35 = ABS(CM(3)-CM(5))                                           CS200630
      CM35SQ = CM35*CM35                                                CS200640
      IF(CM(5).GT.CM(3)) GO TO 200                                      CS200650
      X(11) = 0.                                                        CS200660
      X(17) = 0.                                                        CS200670
      X(25) = 0.                                                        CS200680
      DO 100 I=1,IT                                                     CS200690
      IF(IFLAG(1).EQ.1) X(8) = CM(1)/(C1+X(11)/K(11)+X(17)/K(16))       CS200700
      IF(IFLAG(4).EQ.1) X(23) = CM(4)/(1.+X(11)/K(24)+X(25)/K(25))      CS200710
      F3 = C3+X(17)/K(17)+X(25)/K(29)                                   CS200720
      F5 = C5+X(8)/K(11)+X(23)/K(24)                                    CS200730
      DISC = CM35SQ+4.*K(36)*F5*F3                                      CS200740
      X(10) = (CM35+SQRT(DISC))/(2.*F3)                                 CS200750
      X(11) = K(36)/X(10)                                               CS200760
      IF(IFLAG(6).EQ.0) GO TO 50                                        CS200770
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))                         CS200780
      X(17) = AMIN1(X(17),SOL6)                                         CS200790
   50 CONTINUE                                                          CS200800
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))      CS200810
  100 CONTINUE                                                          CS200820
      F3 = C3+X(11)/K(12)+X(17)/K(17)+X(25)/K(29)                       CS200830
      RETURN                                                            CS200840
  200 CONTINUE                                                          CS200850
      X(8) = 0.                                                         CS200860
      X(10) = 0.                                                        CS200870
      X(23) = 0.                                                        CS200880
      DO 250 I=1,IT                                                     CS200890
      IF(IFLAG(6).EQ.0) GO TO 230                                       CS200900
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))                         CS200910
      X(17) = AMIN1(X(17),SOL6)                                         CS200920
  230 CONTINUE                                                          CS200930
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))      CS200940
      F3 = C3+X(17)/K(17)+X(25)/K(29)                                   CS200950
      F5 = C5+X(8)/K(11)+X(23)/K(24)                                    CS200960
      DISC = CM35SQ+4.*K(36)*F5*F3                                      CS200970
      X(11) = (CM35+SQRT(DISC))/(2.*F5)                                 CS200980
      X(10) = K(36)/X(11)                                               CS200990
      IF(IFLAG(1).EQ.1) X(8) = CM(1)/(C1+X(11)/K(11)+X(17)/K(16))       CS201000
  250 CONTINUE                                                          CS201010
      F3 = C3+X(11)/K(12)+X(17)/K(17)+X(25)/K(29)                       CS201020
      RETURN                                                            CS201030
      END                                                               CS201040
C                                                                       CS201050
C                                                                       CS201060
C                                                                       CS201070
C                                                                       CS201080
C                                                                       CS201090
C                                                                       CS201100
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      SUBROUTINE CASOX (IFLAG,K,X,CM,PP,SOL6)                           CS201110
      DIMENSION X(50),CM(10),PP(2),IFLAG(10)                            CS201120
      COMMON/CEE/C1,C3,C5,C6,C7,F1,F3                                   CS201130
      REAL K(50)                                                        CS201140
      IT = 5                                                            CS201150
      IF(IFLAG(4).EQ.0.AND.IFLAG(6).EQ.0.AND.IFLAG(7).EW.0) IT = 1      CS201160
      CM135 = ABS(CM(1)+CM(3)-CM(5))                                    CS201170
      C135SQ = CM135*CM135                                              CS201180
      IF(CM(5).GT.(CM(1)+CM(3))) GO TO 200                              CS201190
      X(11) = 0.                                                        CS201200
      X(17) = 0.                                                        CS201210
      X(25) = 0.                                                        CS201220
      DO 100 I=1,IT                                                     CS201230
      IF(IFLAG(4).EQ.1) X(23) = CM(4)/(1.+X(11)/K(24)+X(25)/K(25))      CS201240
      F1 = C1+X(17)/K(16)                                               CS201250
      F3 = C3+X(17)/K(17)+X(25)/K(29)                                   CS201260
      F5 = C5+X(23)/K(24)                                               CS201270
      THF = F1+F3*K(36)/K(35)                                           CS201280
      DISC = C135SQ+4.*K(35)*F5*THF                                     CS201290
      X(8) = (CM135+SQRT(DISC))/(2.*THF)                                CS201300
      X(11) = K(35)/X(8)                                                CS201310
      X(10) = K(36)/X(11)                                               CS201320
      IF(IFLAG(6).EQ.0) GO TO 50                                        CS201330
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))                         CS201340
      X(17) = AMIN1(X(17),SOL6)                                         CS201350
   50 CONTINUE                                                          CS201360
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))      CS201370
  100 CONTINUE                                                          CS201380
      F1 = C1+X(11)/K(11)+X(17)/K(16)                                   CS201390
      F3 = C3+X(11)/K(12)+X(17)/K(17)+X(25)/K(29)                       CS201400
      RETURN                                                            CS201410
  200 CONTINUE                                                          CS201420
      X(8) = 0.                                                         CS201430
      X(10) = 0.                                                        CS201440
      X(23) = 0.                                                        CS201450
      DO 250 I=1,IT                                                     CS201460
      IF(IFLAG(6).EQ.0) GO TO 230                                       CS201470
      X(17) = CM(6)/(C6+X(8)/K(16)+X(10)/K(17))                         CS201480
      X(17) = AMIN1(X(17),SOL6)                                         CS201490
  230 CONTINUE                                                          CS201500
      IF(IFLAG(7).EQ.1) X(25) = CM(7)/(C7+X(10)/K(29)+X(23)/K(25))      CS201510
      F1 = C1+X(17)/K(16)                                               CS201520
      F3 = C3+X(17)/K(17)+X(25)/K(29)                                   CS201530
      F5 = C5+X(23)/K(24)                                               CS201540
      DISC = C135SQ+4.*F5*(F1*K(35)+F3*K(36))                           CS201550
      X(11) = (CM135+SQRT(DISC))/(2.*F5)                                CS201560
      X(8) = K(35)/X(11)                                                CS201570
      X(10) = K(36)/X(11)                                               CS201580
  250 CONTINUE                                                          CS201590
      F1 = C1+X(11)/K(11)+X(17)/K(16)                                   CS201600
      F3 = C3+X(11)/K(12)+X(17)/K(17)+X(25)/K(29)                       CS201610
      RETURN                                                            CS201620
      END                                                               CS201630
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BEQPRINT FORTRAN  P     ID=BECCL1          12/19/74    10.58.14          PAGE 1
       VP/CSS    ---       NATIONAL CSS, INC. (SUNNYVALE DATA CENTER)


      SUBROUTINE BEQPRT (NOPR,IOPT,IFLAG,TK,X,CM,PP,SS,IPH,PH,FNA)
C**********************************************************************
C****** THIS ROUTINE WRITES OUTPUT FOR SLURRY EQUILIBRIA
C       DETERMINED BY SUBROUTINE BEQ.
C
C**********************************************************************
      DIMENSION X(50),CM(10),PP(2),IFLAG(10),ILA(8),CML(8),CMS(8)
      DIMENSION IC(37), SS(3), CWL(8), CWS(8)
      COMMON/GAMMA/GAM(50)
      COMMON/TEMP/AC,BC,CPK(2),CK(50)
      COMMON /IO/ IDENT(20), CCM(10), CW(10)
      COMMON /INPUT/ PPSO2, PPCO2, SS1, SS3, KK1, JJS, PPH
      REAL*8 CMP(10) /'      CA','      MG','      NA','       K',
     1 '     SO3','     SO4','     CO3','      CL',' ',' '/
      REAL*8 LB(74)
      REAL MW(8)/40.08,24.31,22.99,39.10,80.06,96.06,60.01,35.45/
C
      DATA  LB/6HH+    ,6H      ,6HOH-   ,6H      ,6HH2CO3 ,6H      ,
     1 6HHCO3- ,6H      ,6HCO3-- ,6H      ,6HH2SO3 ,6H      ,6HHSO3- ,
     2 6H      ,6HSO3-- ,6H      ,6HHSO4- ,6H      ,6HSO4-- ,6H      ,
     3 6HCA++  ,6H      ,6HCAOH+ ,6H      ,6HCAHCO3,6H+     ,6HCACO3 ,
     4 6H      ,6HCASO3 ,6H      ,6HCASO4 ,6H      ,6HMG++  ,6H      ,
     5 6HMGOH+ ,6H      ,6HMGHCO3,6H+     ,6HMGCO3 ,6H      ,6HMGSO3 ,
     6 6H      ,6HMGSO4 ,6H      ,6HNO3-  ,6H      ,6HCANO3+,6H      ,
     7 6HNA+   ,6H      ,6HNANO3 ,6H      ,6HNAOH  ,6H      ,6HNAHCO3,
     8 6H      ,6HNACO3-,6H      ,6HNASO4-,6H      ,6HCL-   ,6H      ,
     9 6HCACO3 ,6H(S)   ,6HCASO3 ,6H(S)   ,6HCASO4 ,6H(S)   ,6HCA(OH),
     1 6H2 (S) ,6HMGCO3 ,6H(S)   ,6HMG(OH),6H2 (S) /
C
C
      REAL*8 ILA /'CA','MG','NA','K','SO3','SO4','CO3','CL'/
C
      DATA  IC/1,2,3,4,5,3,4,5,2,6,7,2,2,3,3,3,6,2,2,3,3,3,9,
     1 2,10,3,3,3,2,2,11,12,12,12,12,12,12/
C
      IP = NOPR
      PP1 = PP(1)
      PP2 = PP(2)
      WRITE(6,100)
  100 FORMAT(1H0,32X,'BECHTEL MODIFIED RADIAN EQUILIBRIUM PROGRAM'/
     1 1H , 'INPUT DATA:' )
      WRITE (6,150) KK1, JJS, TK, PPSO2, PPCO2, SS1, SS3, IPH, PPH
150   FORMAT(1H , 3X, 'K1', 4X, 'JS', 4X, 'TK', 6X, 'PPSO2', 8X,'PPCO2',
     1 7X, 'SSO3', 5X, 'SSO4', 3X, 'IPH', 4X, 'PH' /
     2 1H , 1X, I4,2X,I4,2X, F6.1,2X, G10.4,2X, G10.4,2X, F7.3,2X,F7.3,
     3 3X, I3, 1X, F7.3 )
      WRITE (6,160) (CMP(I), I=1,8)
160   FORMAT( 1H0, 3X,'CONCENTRATIONS, GMOL/LITER AND PPM(WT):' /
     1 1H ,7(A8,1X),A8)
      WRITE (6,170) (CCM(I), I=1,8)
170   FORMAT( 1H , 7(F8.5, 1X), F8.5)
      WRITE (6,180) (CW(I), I=1,8)
  180 FORMAT(1H ,7(F8.0,1X),F8.0)
      IF(IFLAG(1).EQ.0) CM1 = X(6)+X(7)+X(8)+X(15)+X(21)+X(33)
      IF(IFLAG(2).EQ.0) CM2 = X(3)+X(4)+X(5)+X(13)+X(14)+X(19)+X(20)
     1 +X(28)+X(29)+X(32)+X(36)
      IF(IP.NE.1) GO TO 1220
      WRITE(6,1100)
 1100  FORMAT( / 1H , 'CALCULATED RESULTS:', 12X, 'CONCENTRATION' /
     1         1H ,14X,'COMPONENT',8X,'GMOL/LITER',  10X,'ACTIVITY COEFFIC
     2IENT'/)
      DO 1300 I=1,37
      IF(X(I).LE.0.) GO TO 1300
      IS = 2*I-1
      IG = IC(I)
      WRITE(6,1200) LB(IS),LB(IS+1),X(I),GAM(IG)
 1300 CONTINUE
 1200 FORMAT(15X,A6,A6,F15.4,13X,F7.4)
      GO TO 1304
 1220 CONTINUE
      IF(IOPT.EQ.2.OR.IOPT.EQ.3) GO TO 1260
      WRITE(6,1240) PH,PP2
 1240 FORMAT(/1H ,'PH = ',F6.3,8X,'PPCO2 = ',G10.4,' ATM'/)
      GO TO 2300
 1260 CONTINUE
      WRITE(6,1280) PH,CM2
 1280 FORMAT(/1H ,'PH = ',F6.3,8X,'CO2 = ',F9.6,' GMOL/L'/)
      GO TO 2300
 1304 CONTINUE
      IF(IOPT.EQ.1) GO TO 1330
      IF(IOPT.EQ.2) GO TO 1350
      IF(IOPT.EQ.3) GO TO 2100
      WRITE(6,1310) PH,PP1,PP2
 1310 FORMAT(/1H ,'PH = ',F6.3,8X,'PPSO2 = ',G10.4,' ATM',8X,'PPCO2 = ',
     1 G10.4, ' ATM'/)
      GO TO 2300
 1330 CONTINUE
      WRITE(6,1340) PH,CM1,PP2
 1340 FORMAT(/1H ,'PH = ',F6.3,8X,'SO2 = ',F9.6,' GMOL/L',8X,'PPCO2 = ',
     1 G10.4, ' ATM'/)
      GO TO 2300
 1350 CONTINUE
      WRITE(6,1400) PH,PP1,CM2
 1400 FORMAT(/1H ,'PH = ',F6.3,8X,'PPSO2 = ',G10.4,' ATM',8X,'CO2 = ',
     1 F9.6, ' GMOL/L' /)
      GO TO 2300
 2100 CONTINUE
      WRITE(6,2200) PH,CM1,CM2
 2200 FORMAT(/1H ,'PH = ',F6.3,8X,'SO2 = ',F9.6,' GMOL/L',8X,'CO2 = ',
     1 F9.6, ' GMOL/L'/)
 2300 CONTINUE
      IF(IPH.EQ.0) GO TO 2380
      DEL = 2.*(X(11)+X(17))+X(1)+X(12)+X(13)+X(18)+X(19)+X(24)+X(25)
     1 -2.*(X(5)+X(8)+X(10))-(X(2)+X(4)+X(7)+X(9)+X(23)+X(29)
     3 +X(30)+X(31))
      ANF = 2.*(CM(5)+CM(6))+CM(7)
      PCTE = 100.*DEL/ANF
      WRITE(6,2360) PCTE
 2360 FORMAT( 1H ,'PERCENT ERROR IN IONIC BALANCE = ',F6.1)
 2380 CONTINUE
```

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      SS(3) = 100. * SS(3)
      SS(1) = 100. * SS(1)
      IF(IP.EQ.1) GO TO 2395
      WRITE(6,2385) SS(3)
 2385 FORMAT(1H0,'PERCENT SULFATE SATURATION = ',F6.1)
      GO TO 2398
 2395 CONTINUE
      WRITE (6, 2390) SS(3), CK(26)
 2390 FORMAT(1H0, 'PERCENT SULFATE SATURATION = ', F6.1, 8X, '( KSP = '
     1 ,E10.4, ' )' )
 2398 CONTINUE
      DO 2399 I=1,8
      CML(I) = 0.
      CMS(I) = 0.
 2399 CONTINUE
      EPS = 1.E-6
      CML(1) = X(11)+X(12)+X(13)+X(14)+X(15)+X(16)+X(24)
      CMS(1) = X(32)+X(33)+X(34)+X(35)
      CML(2) = X(17)+X(18)+X(19)+X(20)+X(21)+X(22)
      CMS(2) = X(36)+X(37)
      SUMX = X(25)+X(26)+X(27)+X(28)+X(29)+X(30)
      CML(3) = FNA*SUMX
      CML(4) = (1.-FNA)*SUMX
      CML(5) = X(6)+X(7)+X(8)+X(15)+X(21)
      CMS(5) = X(33)
      CML(6) = X(9)+X(10)+X(16)+X(22)+X(30)
      CMS(6) = X(34)
      CML(7) = X(3)+X(4)+X(5)+X(13)+X(14)+X(19)+X(20)+X(28)+X(29)
      CMS(7) = X(32)+X(36)
      CML(8) = X(31)
      CMLTOT = 0.
      CMSTOT = 0.
      CWLTOT = 0.
      CWSTOT = 0.
      DO 2410 I=1,8
      CMLTOT = CMLTOT + CML(I)
      CMSTOT = CMSTOT + CMS(I)
      CWL(I) = 1000. * CML(I) * MW(I)
      CWS(I) = 1000. * CMS(I) * MW(I)
      CWLTOT = CWLTOT + CWL(I)
      CWSTOT = CWSTOT + CWS(I)
2410  CONTINUE
      CWTOT = 0.
      IF(IOPT.GT.1) CW(7) = CM2*1000.*MW(7)
      IF(IOPT.EQ.1.OR.IOPT.EQ.3) CW(5) = CM1*1000.*MW(5)
      DO 2420  I=1,8
2420  CWTOT = CWTOT + CW(I)
      TDS = CWTOT - CWSTOT
      WRITE (6,2450) TDS
2450  FORMAT(1H0, 'TOTAL DISSOLVED SOLIDS = ', F8.0, ' PPM')
      IF(IP.NE.1) GO TO 2600
      WRITE(6,2400)
2400  FORMAT(1H0, 'ANALYSIS OF SLURRY:', 11X, 'LIQUID', 19X,
     1 'SOLID' /
     2 1H , 30X, 'GMOL/LITER', 7X, 'PPM', 5X, 'GMOL/LITER', 10X, 'PPM')
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BEUPRINT FORTRAN  P      ID=HFCCL1           12/19/74    10.58.14          PAGE 4

      DO 2440 I=1,A
      IF(CML(I).LT.1.E-20.AND.CMS(I).LT.1.E-20) GO TO 2440              LPR01660
      WRITE (6,2500) ILA(I), CML(I), CWL(I), CMS(I), CWS(I)              LPR01670
 2440 CONTINUE                                                           LPR01680
 2500 FORMAT(1H , 21X, A8, E12.4, F10.0, 5X, E12.4, F10.0)               LPR01690
 2600 CONTINUE                                                           LPR01700
      RETURN                                                             LPR01710
      END                                                                LPR01720
                                                                         LPR01730
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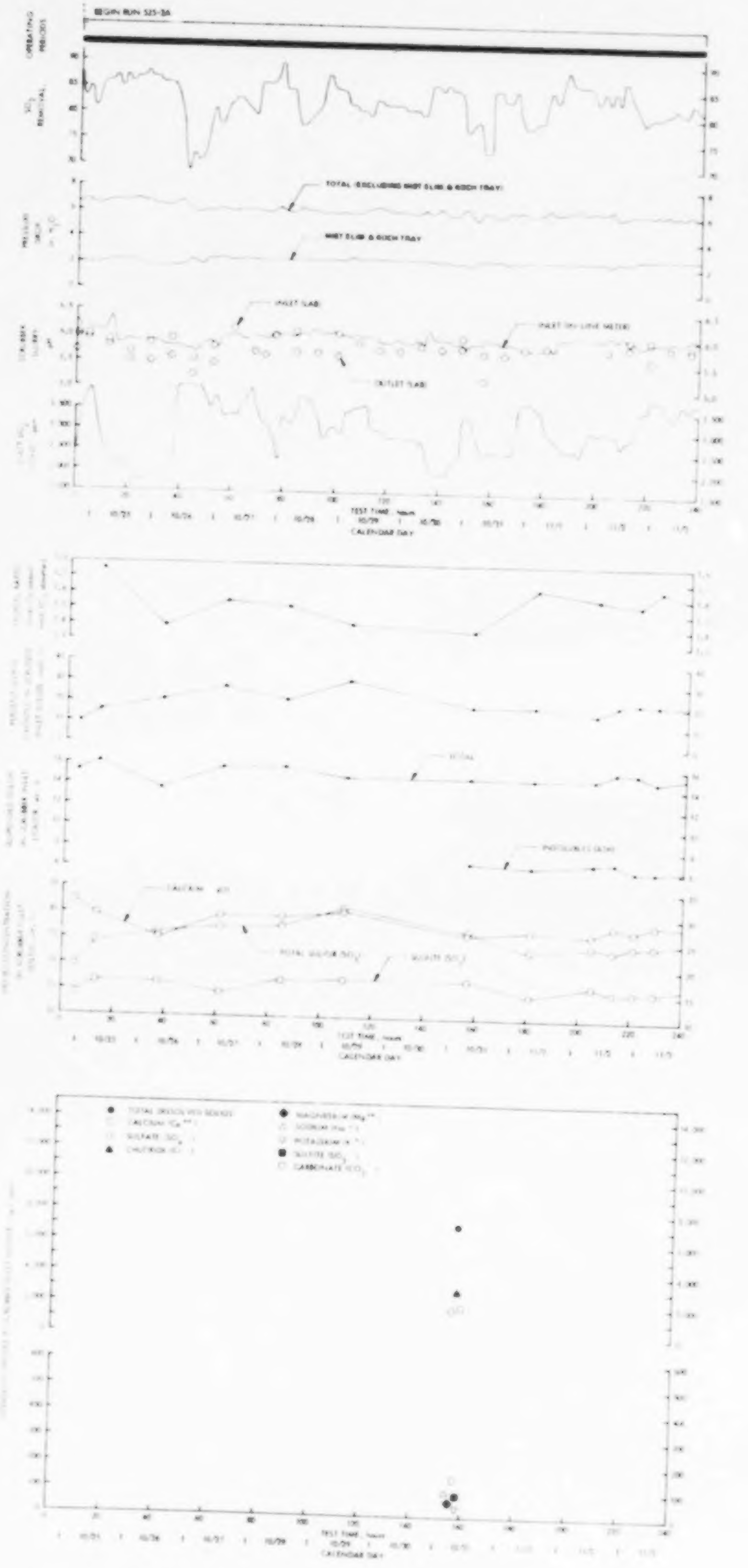
Appendix H

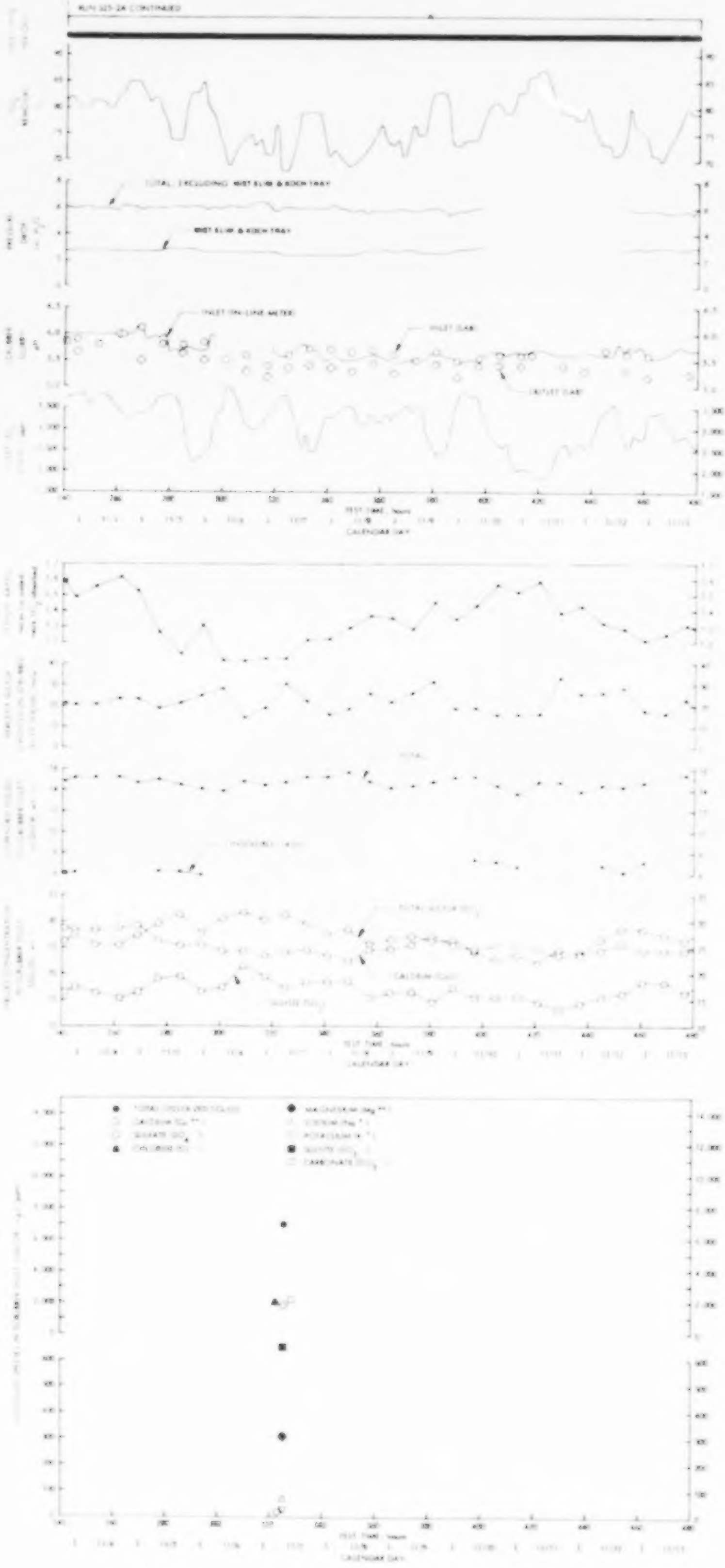
GRAPHICAL OPERATING DATA FROM LIMESTONE RELIABILITY TESTS



Gas Rate = 25,000 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 64 gal/mcf
Gas Velocity = 9.8 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 122-126 °F
Liquid Conductivity = 3,200-7,500 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 27-41 wt %

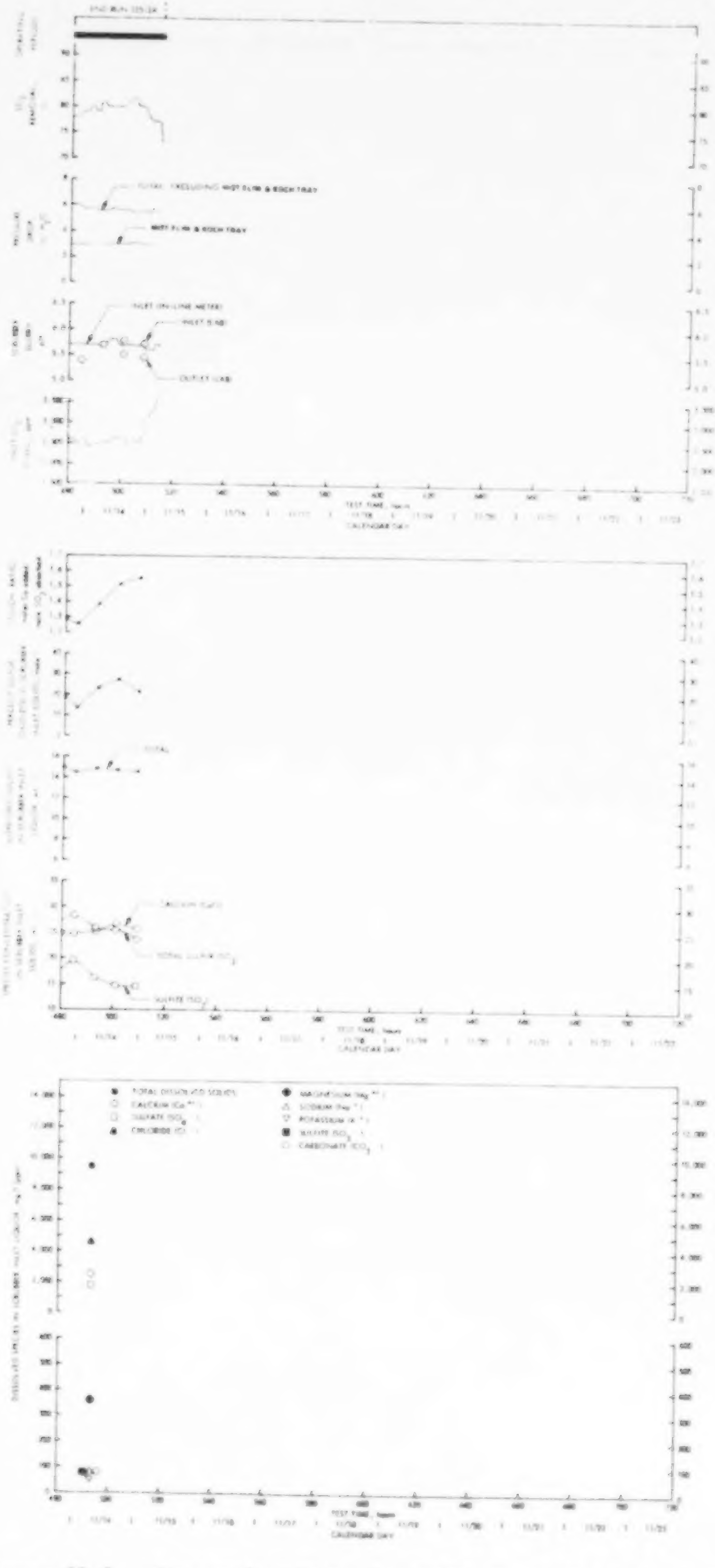
Figure H-1. Operating Data for TCA Run 525-2A



Gas Rate = 25,000 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 64 gal/mcf
Gas Velocity = 9.8 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 119-123 °F
Liquid Conductivity = 7,500-9,300 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 31-42 wt %

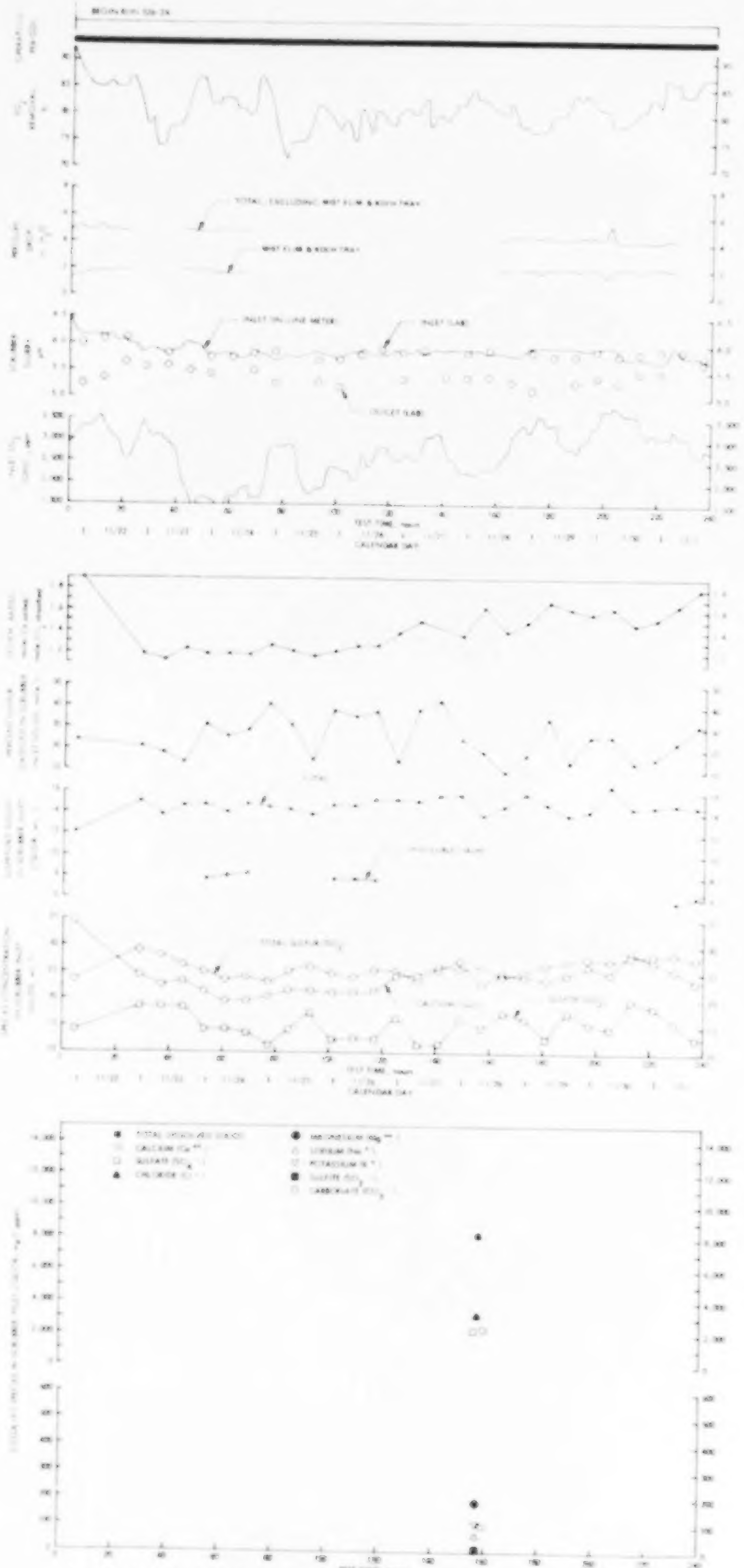
Figure H-1. Operating Data for TCA Run 525-2A (continued)



Gas Rate = 25,000 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 64 gal/mcf
Gas Velocity = 9.8 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. 122-124 °F
Liquid Conductivity = 9,200-10,900 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 40-42 wt %

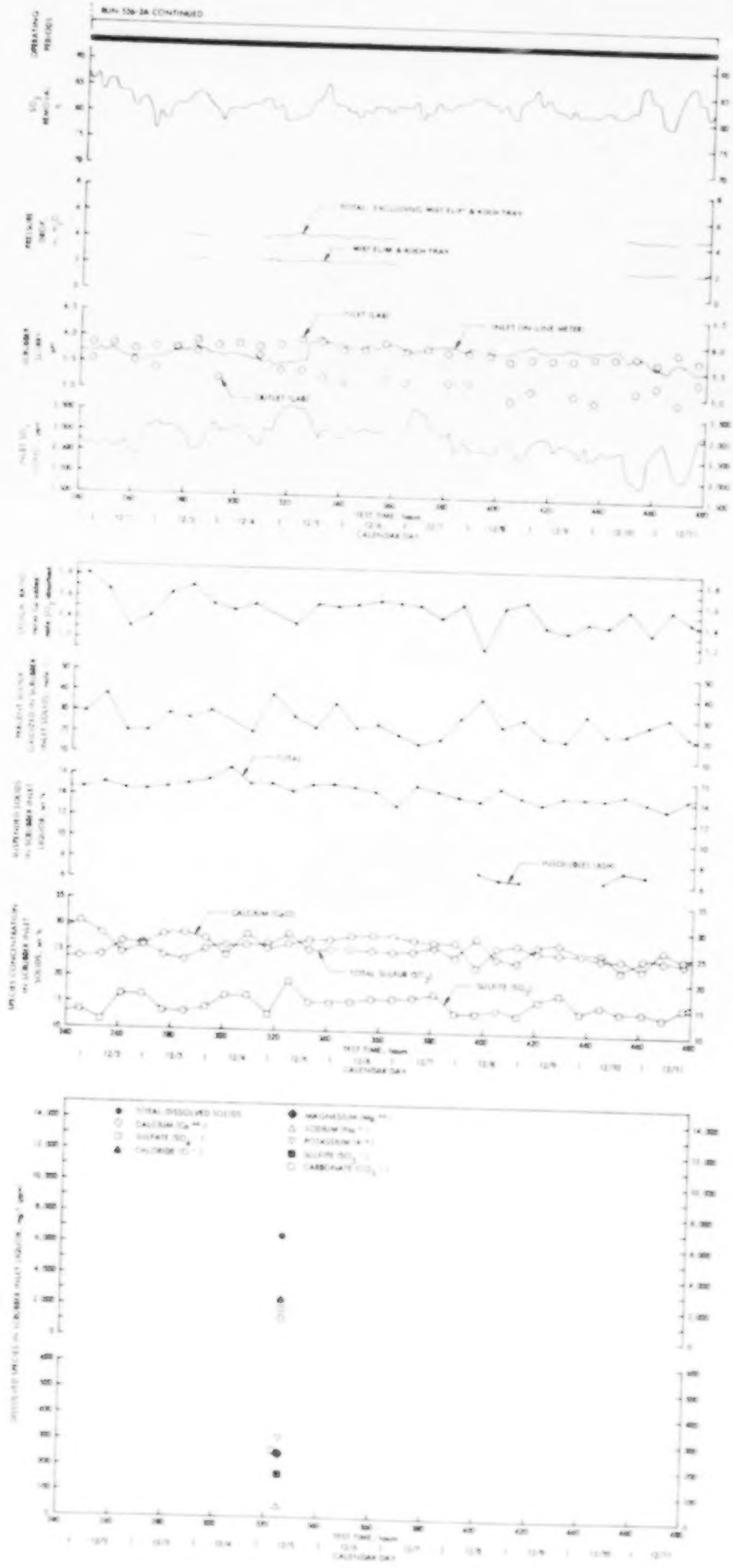
Figure H-1. Operating Data for TCA Run 525-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. 120-124 °F
Liquid Conductivity = 7,000-9,100 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 38-49 wt %

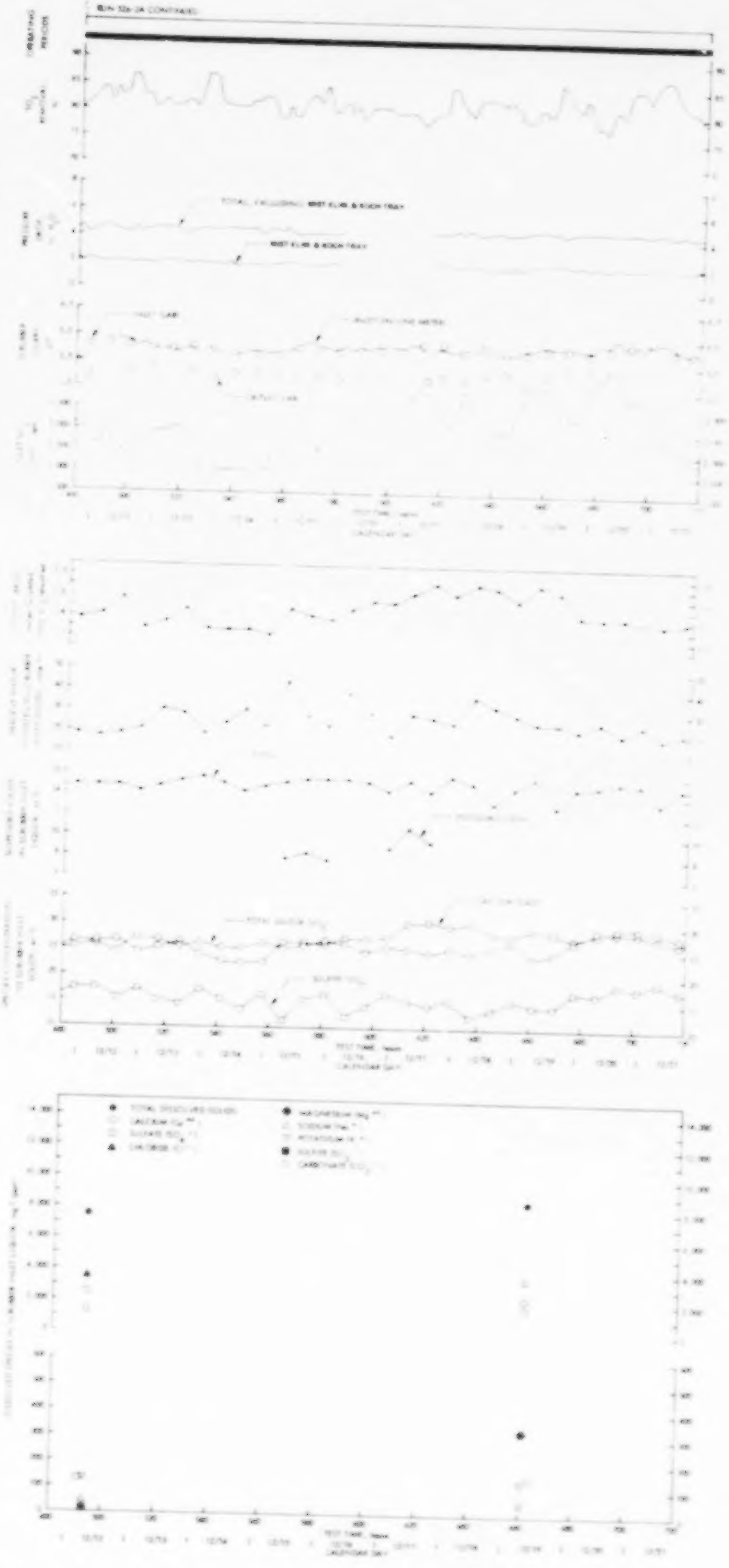
Figure H-2. Operating Data for TCA Run 526-2A



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 118-123 °F
Liquid Conductivity = 6,000-9,900 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 35-44 wt %

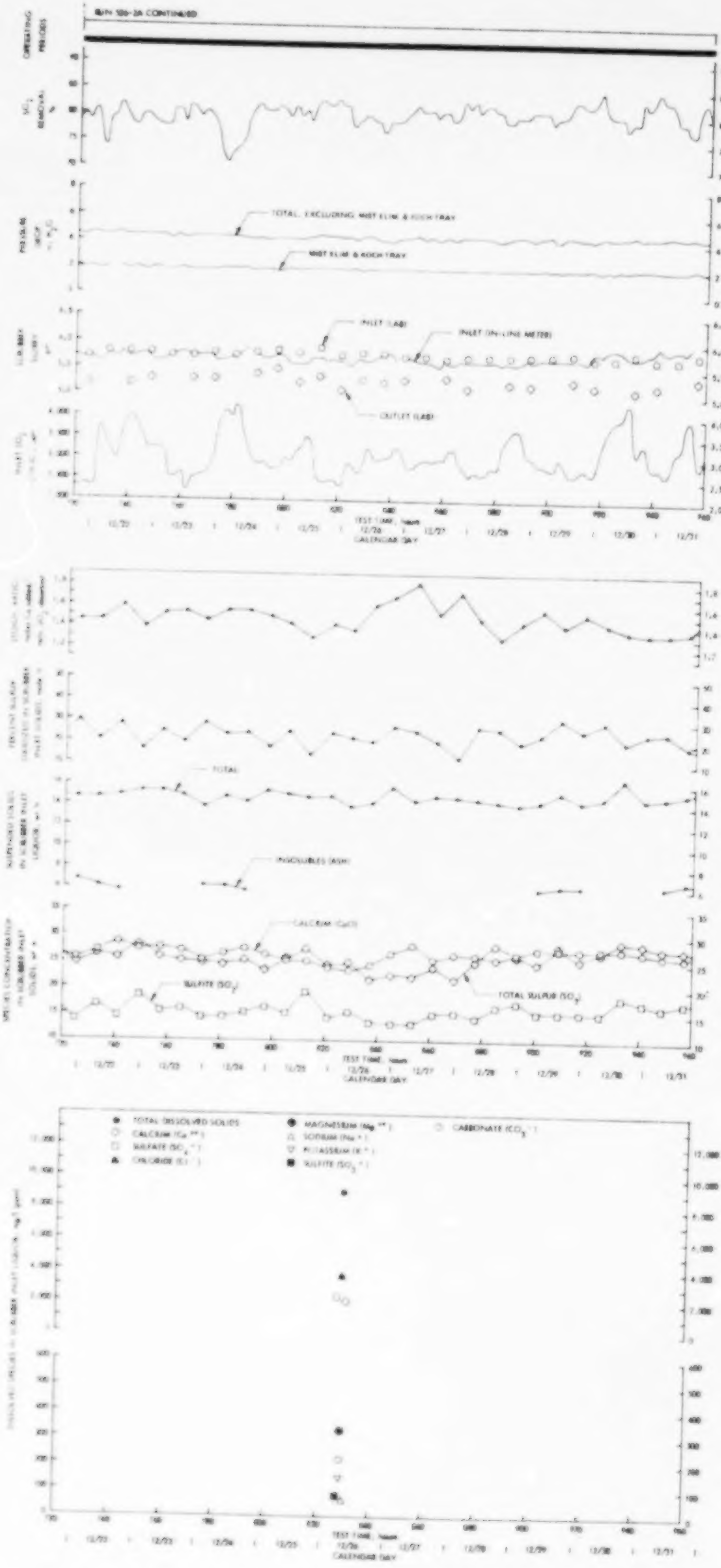
Figure H-2. Operating Data for TCA Run 526-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 70 gal/mcf
Gas Velocity = 8.0 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 120-124 °F
Liquid Conductivity = 7,400-11,500 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 37-46 wt %

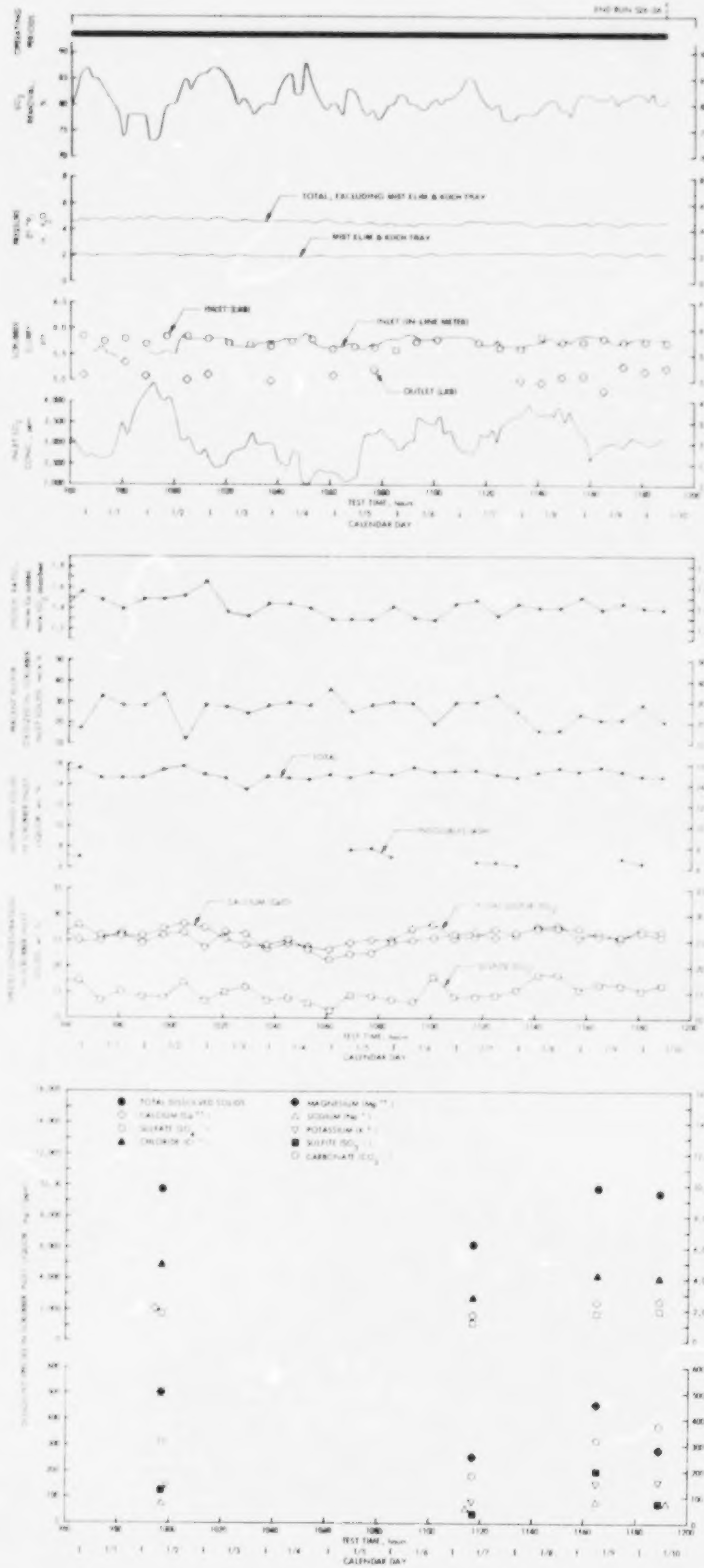
Figure H-2. Operating Data for TCA Run 526-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 118-125 °F
Liquid Conductivity = 7,00-11,100 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 37-47 wt %

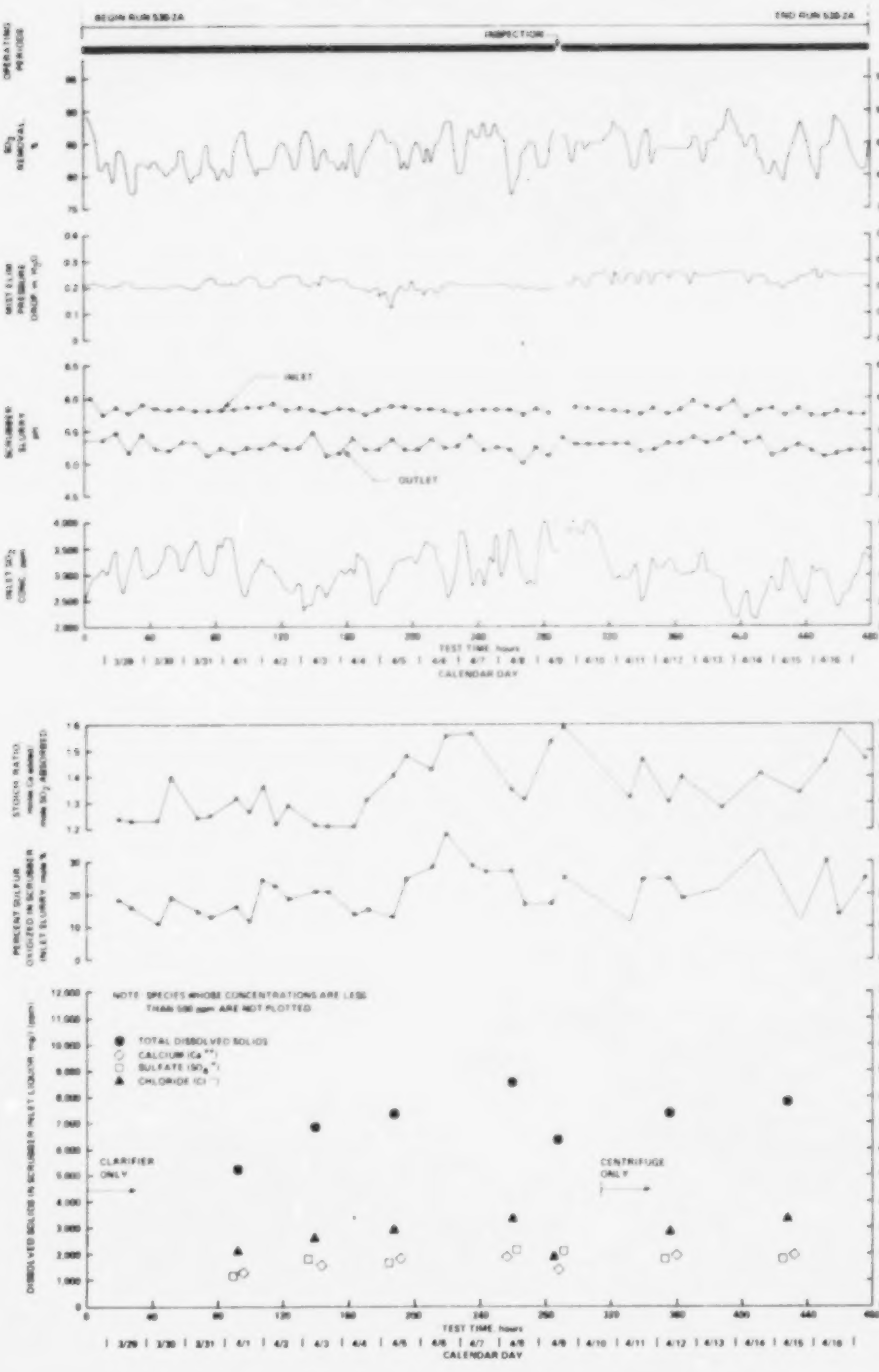
Figure H-2. Operating Data for TCA Run 526-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
Effluent Residence Time = 10 min
Three Stages, 5 in spheres/stage

Scrubber Inlet Liquor Temp. = 118-125 °F
Liquid Conductivity = 7,100-10,400 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 38-46 wt %

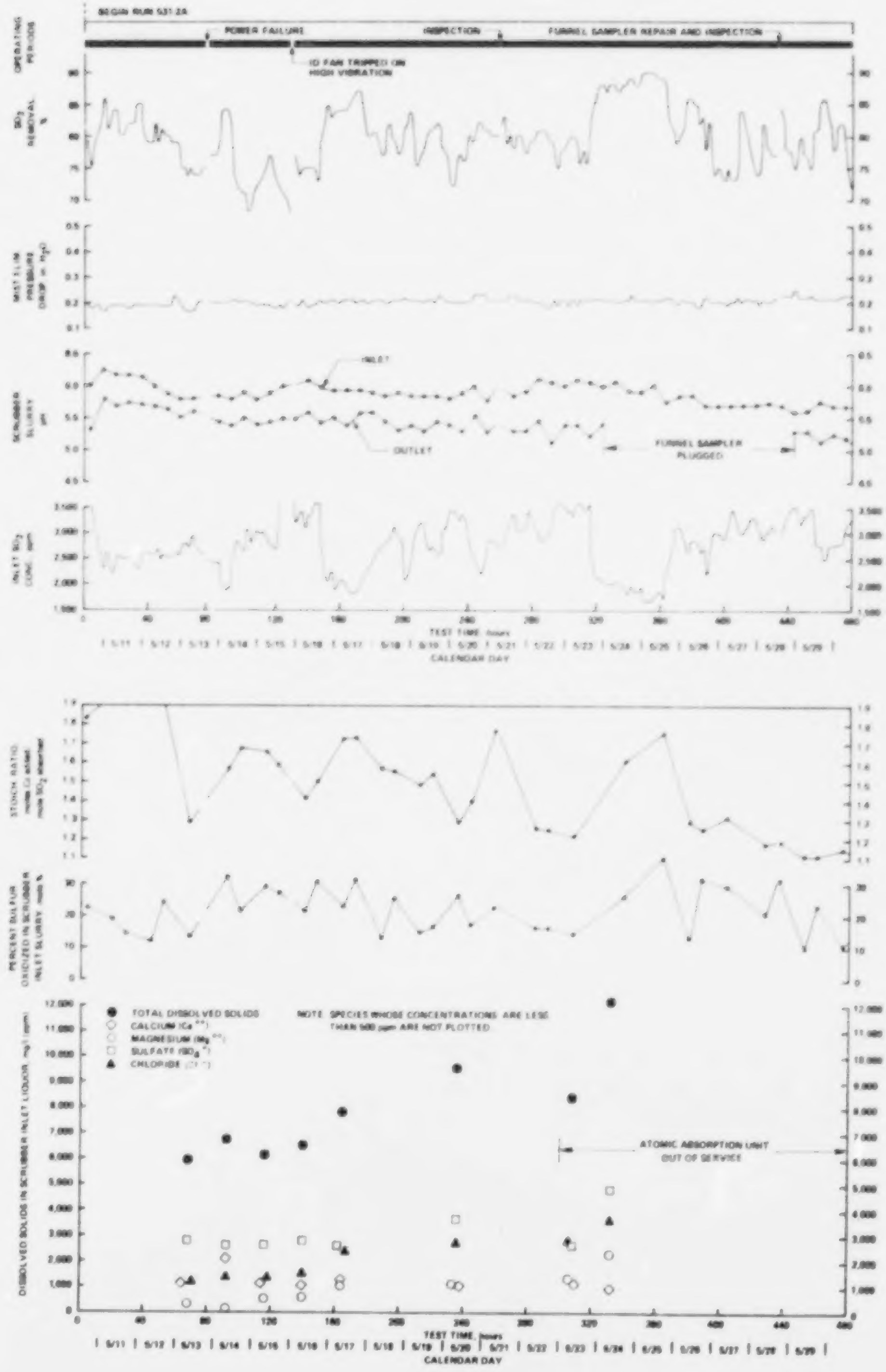
Figure H-2. Operating Data for TCA Run 526-2A (continued)



Gas Rate = 20,500 acfm @ 300°F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 14-16 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.8-5.1 in H_2O
Demister and Koch Tray Pressure Drop = 1.9-2.1 in H_2O
Scrubber Inlet Liquor Temperature = 119-125 °F
Liquid Conductivity = 5,200-8,300 μ mhos/cm
Discharge (Clarifier and Centrifuge) Solids
Concentration = 30-43 wt %

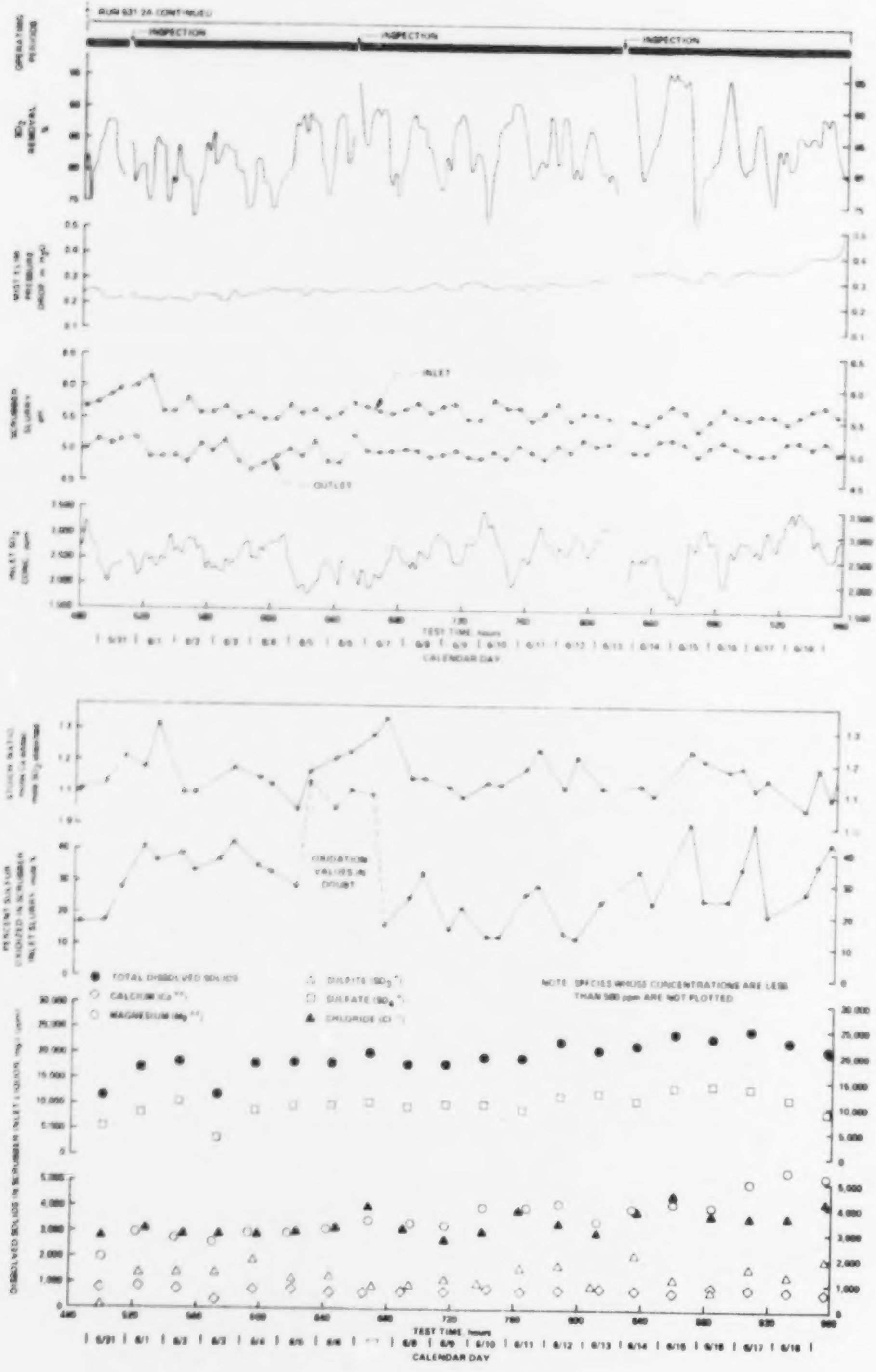
Figure H-3. Operating Data for TCA Run 530-2A



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.8 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 7-9 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.3-6.0 in H_2O
Scrubber Inlet Liquor Temperature = 122-127 °F
Liquid Conductivity = 4,000-10,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 35-42 wt %

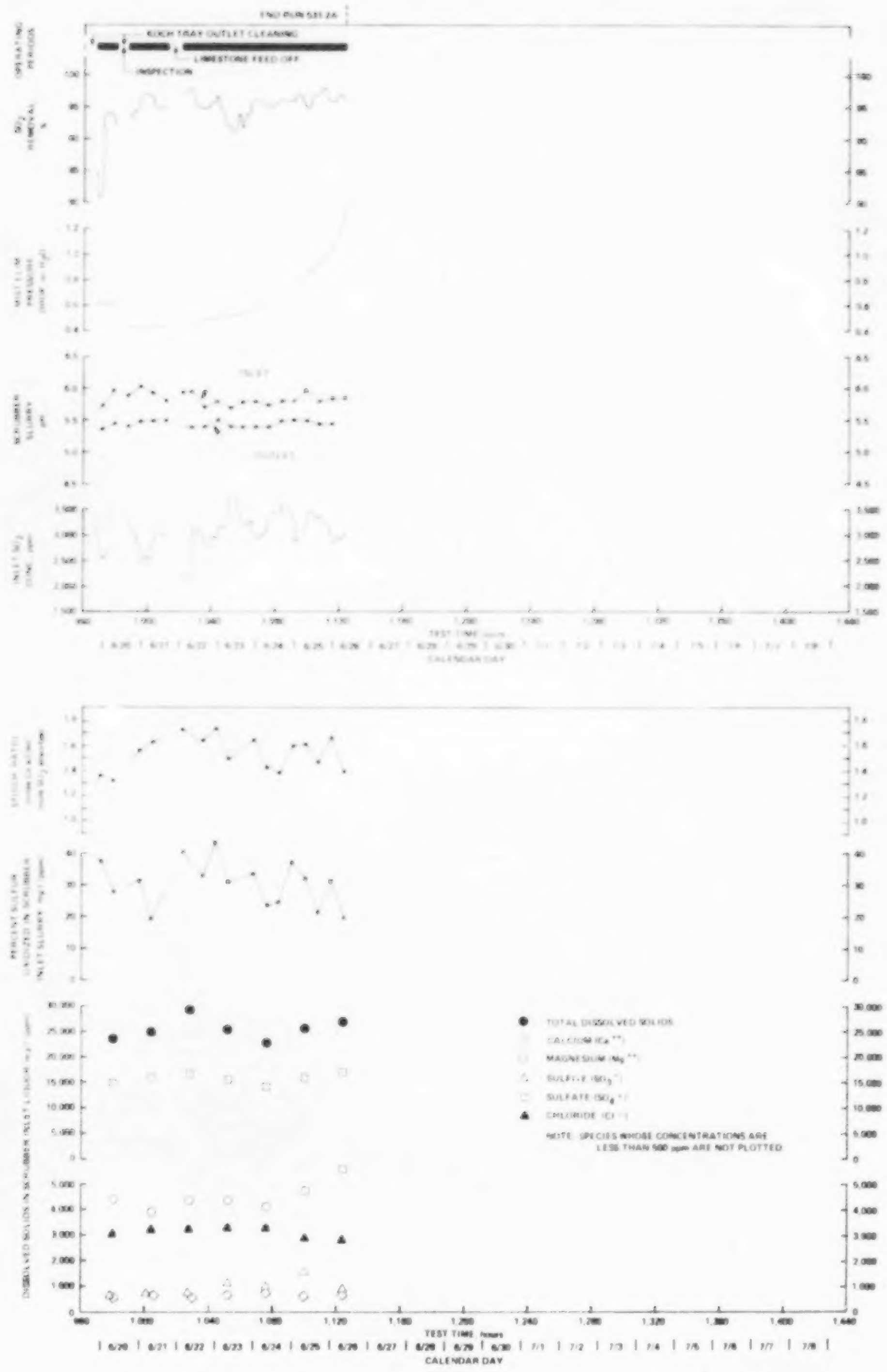
Figure H-4. Operating Data for TCA Run 531-2A



Gas Rate = 23,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
EHT (Sealec) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 7-9 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 6.0-6.6 in H_2O
Scrubber Inlet Liquor Temperature = 122-128 °F
Liquid Conductivity = 10,000-23,000 μ mhr
Discharge (Clarifier) Solids
Concentration = 35-42 wt %

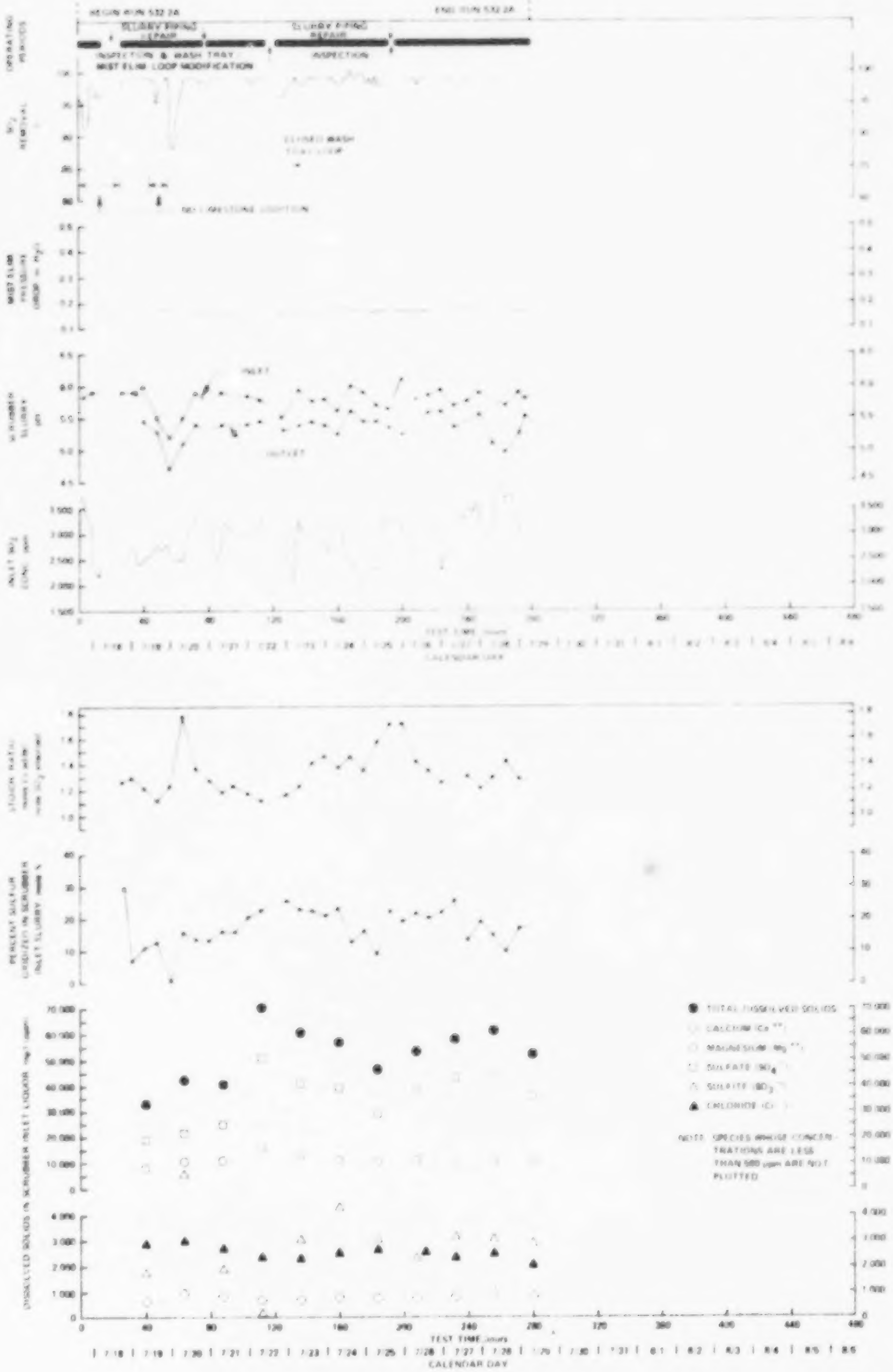
Figure H-4. Operating Data for TCA Run 531-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 7-9 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 6.6-9.5 in H_2O
Scrubber Inlet Liquor Temperature = 122-128 °F
Liquid Conductivity = 22,000-27,500 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 35-42 wt %

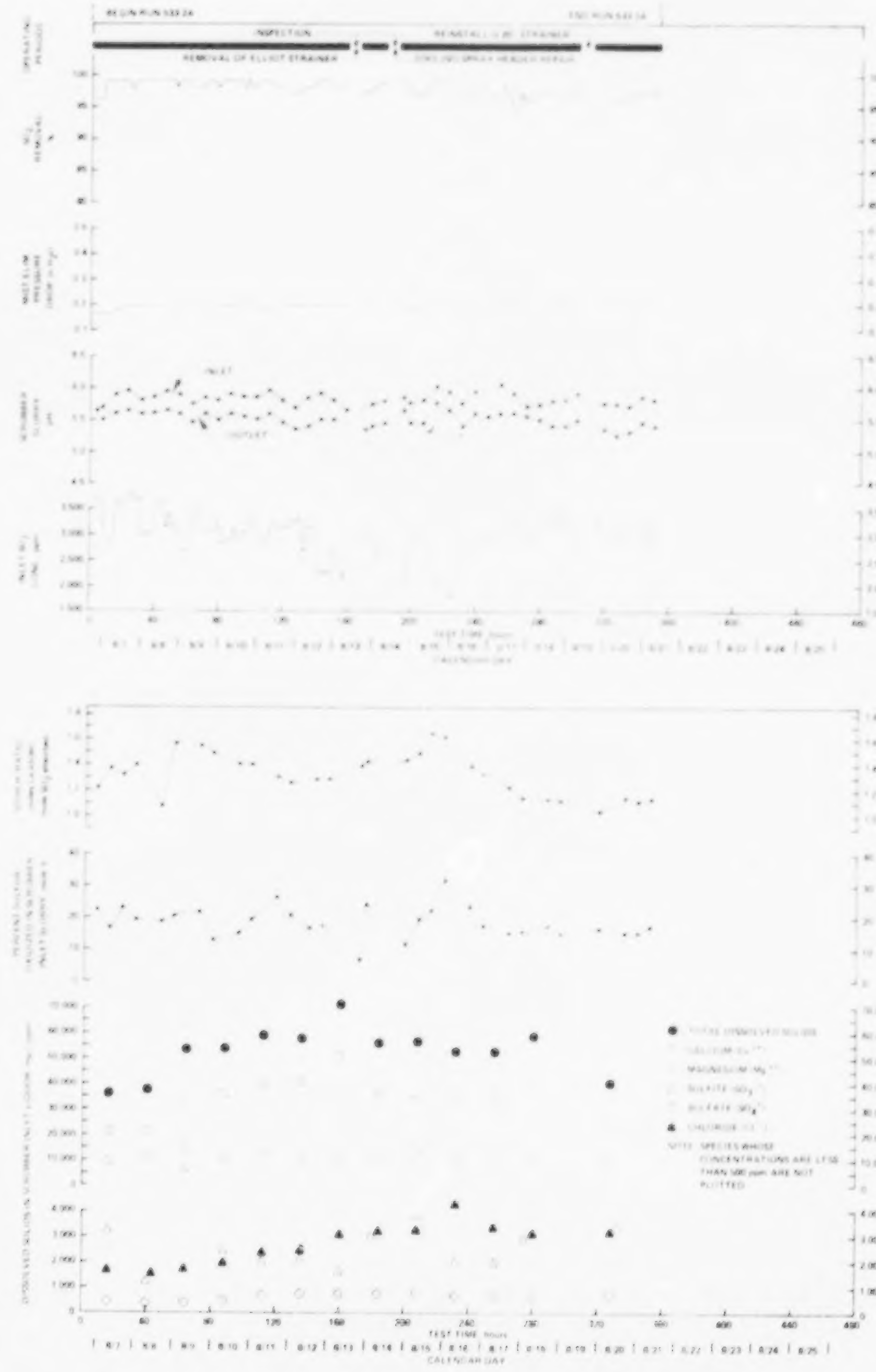
Figure H-4. Operating Data for TCA Run 531-2A (continued)



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 7-9 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.5-4.8 in H_2O
Scrubber Inlet Liquor Temperature = 124-129 °F
Liquid Conductivity = 19,000-26,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 32-43 wt %

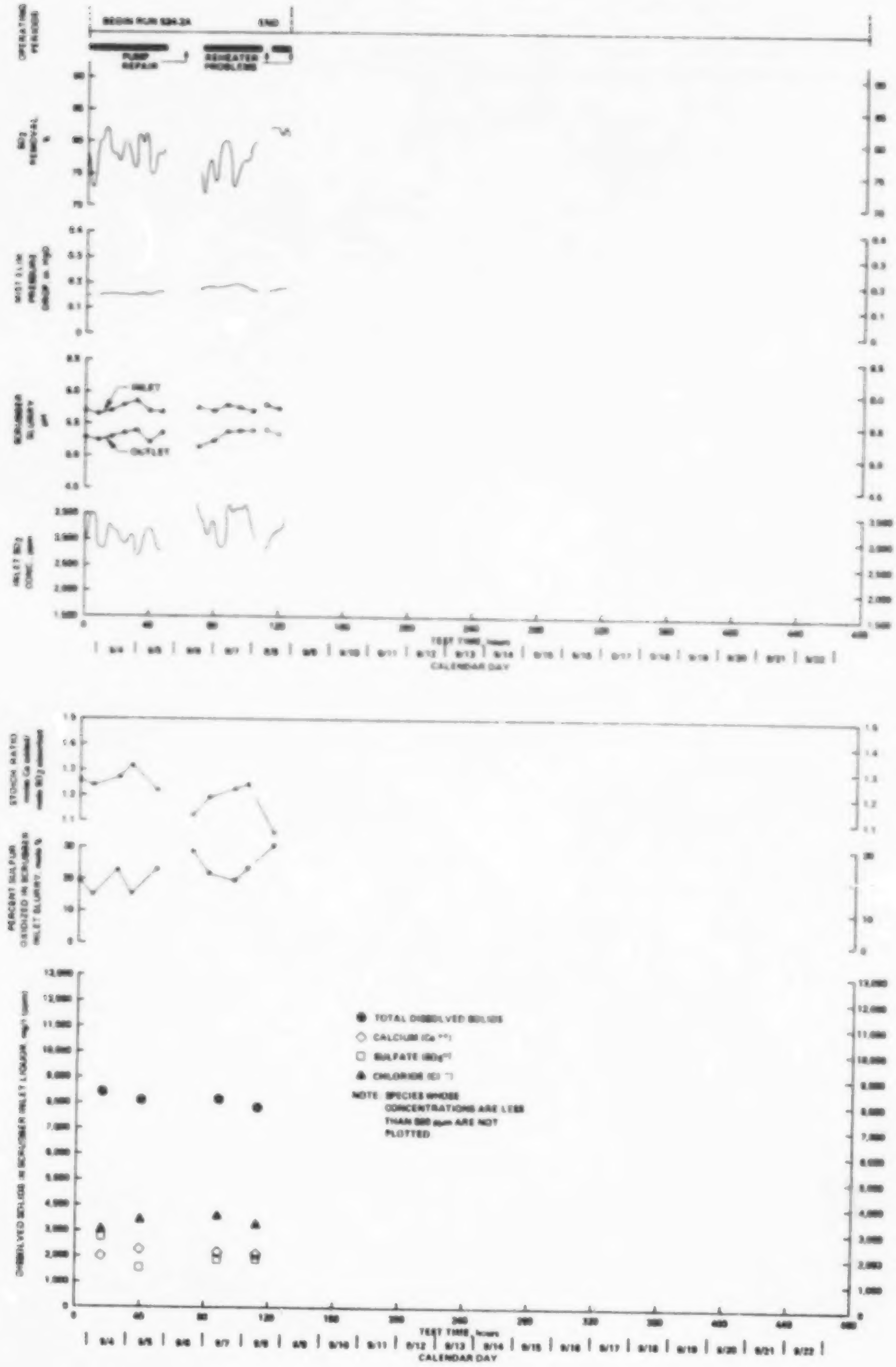
Figure H-5. Operating Data for TCA Run 532-2A



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 78 gal/mcf
Gas Velocity = 8.0 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 14.4-5.5 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.6-4.95 in H_2O
Scrubber Inlet Liquor Temperature = 126-131 °F
Liquid Conductivity =27,000-39,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 29-38 wt %

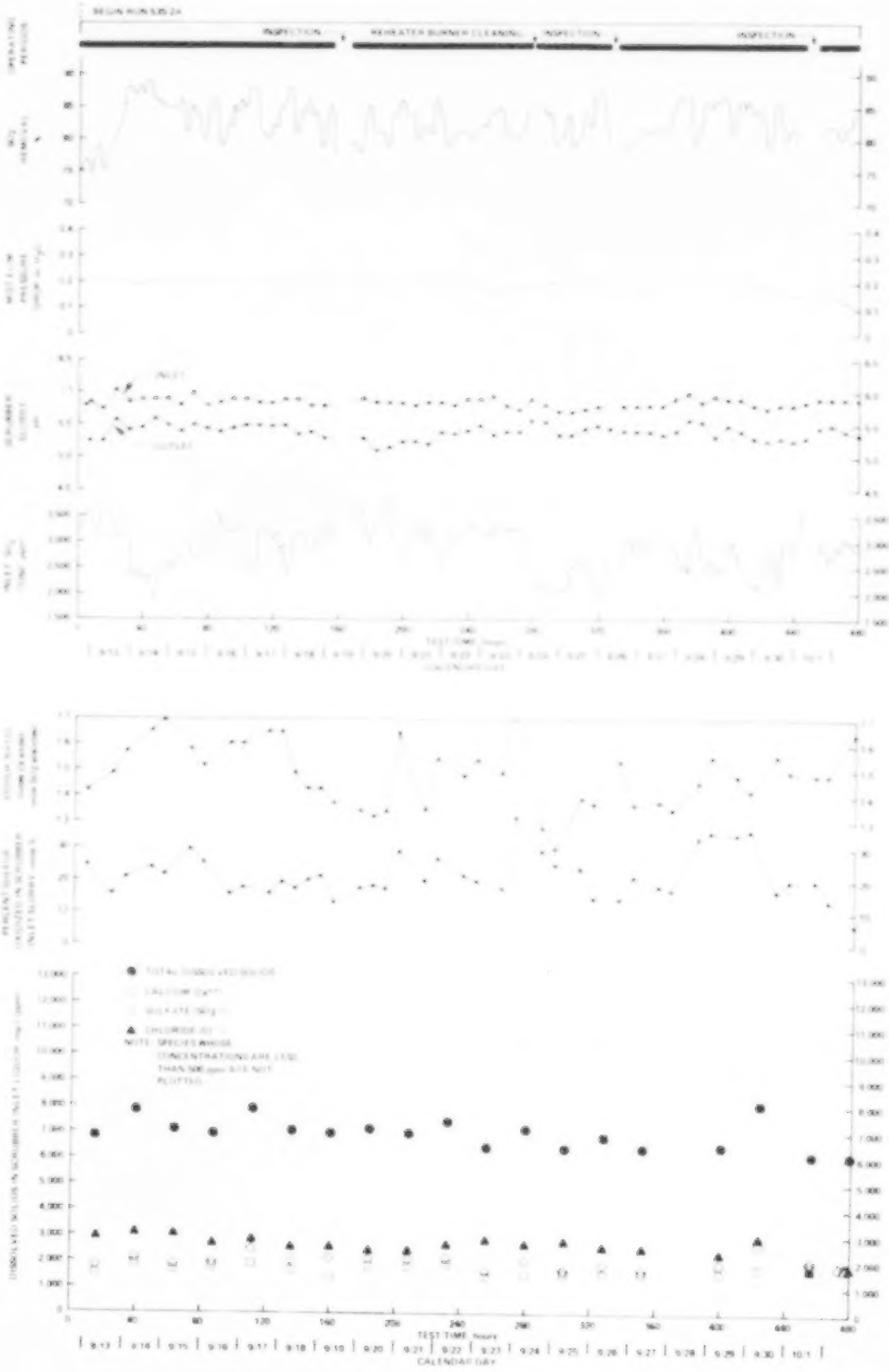
Figure H-6. Operating Data for TCA Run 533-2A



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 73 gal/mcf
Gas Velocity = 8.6 ft/sec
EHT (Sealed) Residence Time = 12 min
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 10-12.5 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.0-4.3 in H_2O
Scrubber Inlet Liquor Temperature = 123-127 °F
Liquid Conductivity = 6,300-9,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 30-40 wt %

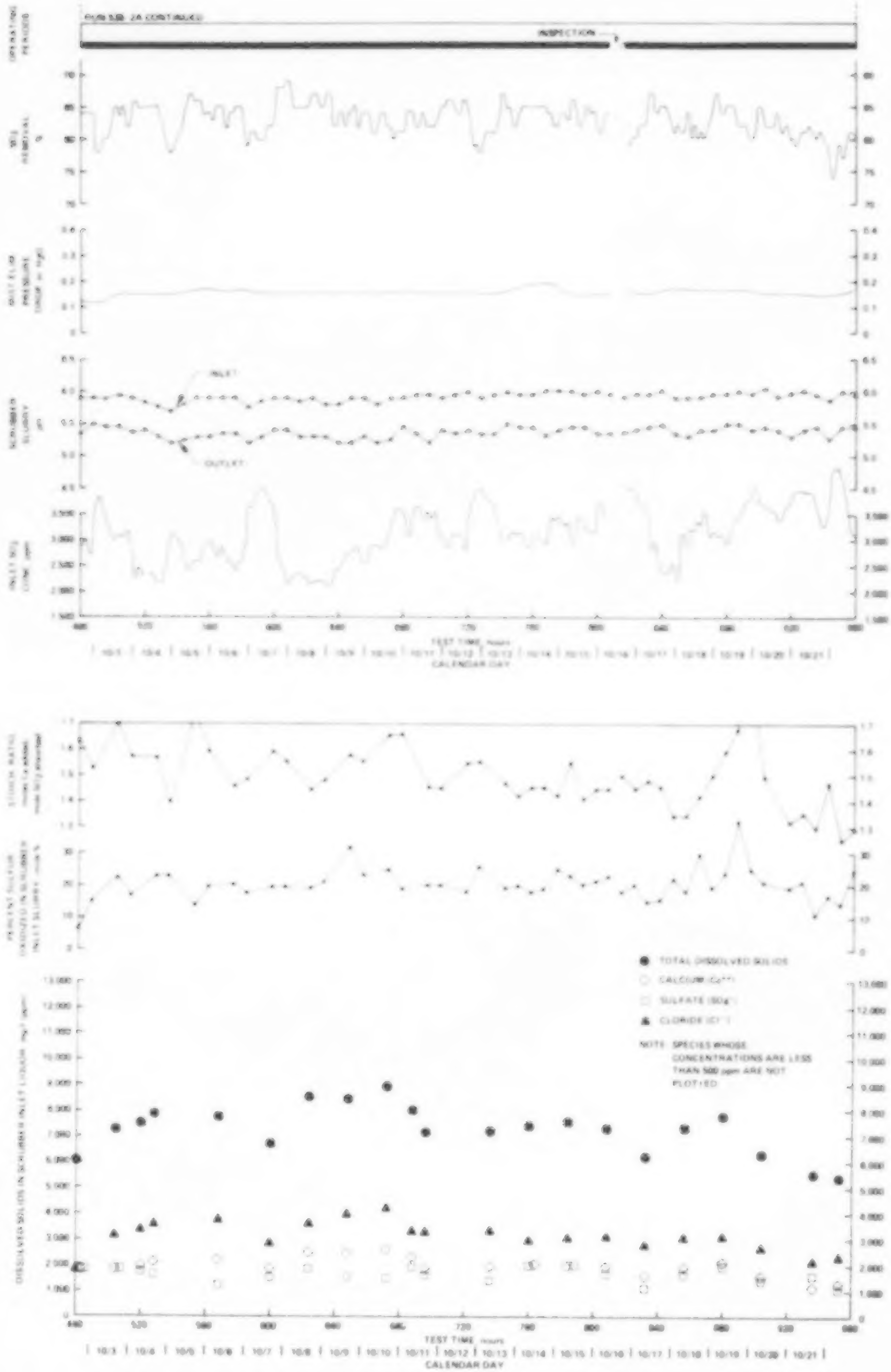
Figure H-7. Operating Data for TCA Run 534-2A



Gas Rate = 20,500 acfm @ 300 °F
Liquor Rate = 1200 gpm
L/G = 73 gal/mcf
Gas Velocity = 8.6 ft/sec
EHT (Sealed) Residence Time = 12 min (9/12-9/27),
15 min (after 9/27)
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 12-15 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.0-4.6 in H_2O
Scrubber Inlet Liquor Temperature = 120-126 °F
Liquid Conductivity = 4,800-10,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 35-42 wt %

Figure H-8. Operating Data for TCA Run 535-2A



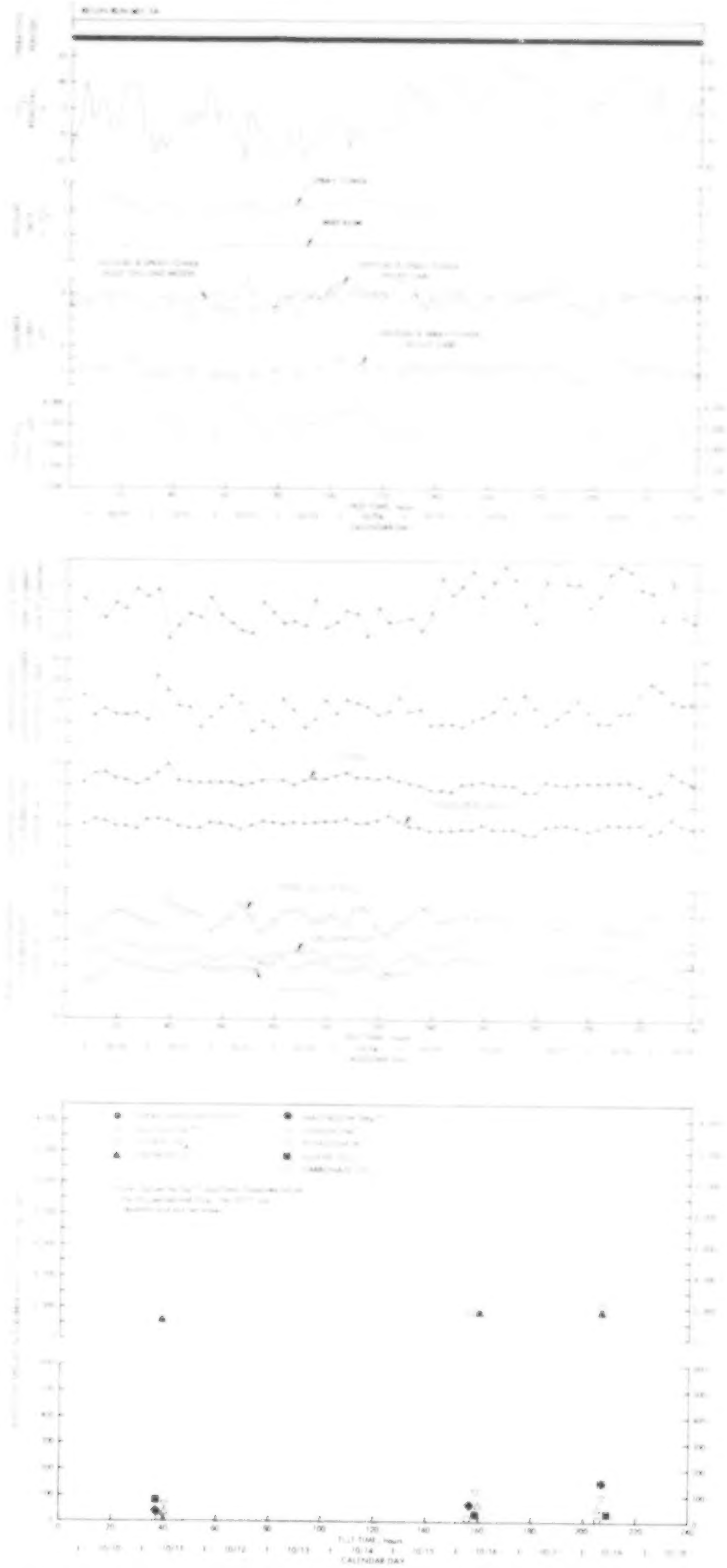
Gas Rate = 20,500 acfm @ 300° F
Liquor Rate = 1200 gpm
L/G = 73 gal/mcf
Gas Velocity = 8.6 ft/sec
EHT (Sealed) Residence Time = 12 min (9/12/27),
15 min (after 9/27)
Three Stages, 5 in spheres/stage

Percent Solids Recirculated = 12-15 wt %
Total Pressure Drop, Excluding Mist Elim.
and Koch Tray = 4.0-4.6 in H_2O
Scrubber Inlet Liquor Temperature = 121-128° F
Liquid Conductivity = 6,500-11,800 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 35-42 wt %

Figure H-9. Operating Data for TCA 535-2A (continued)

Appendix I

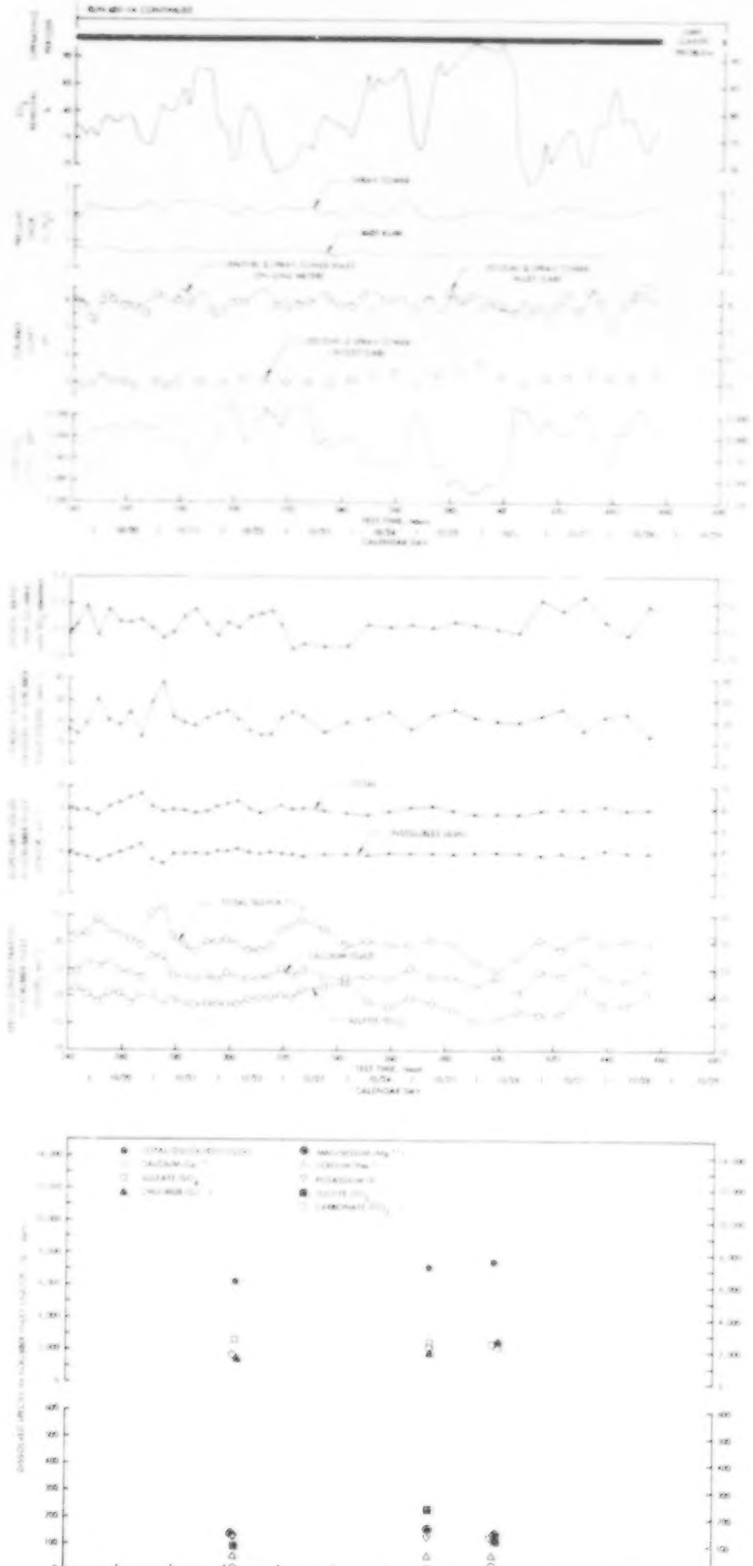
GRAPHICAL OPERATING DATA FROM LIME RELIABILITY TESTS



Gas Rate = 25,000 acfm @ 130 °F
Liquor Rate to Venturi = 800 gpm
Liquor Rate to Spray Tower = 1600 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in. H_2O
E.H.T. Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 125-128 °F
Liquid Conductivity = 3,700-5,200 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 21-26 wt %

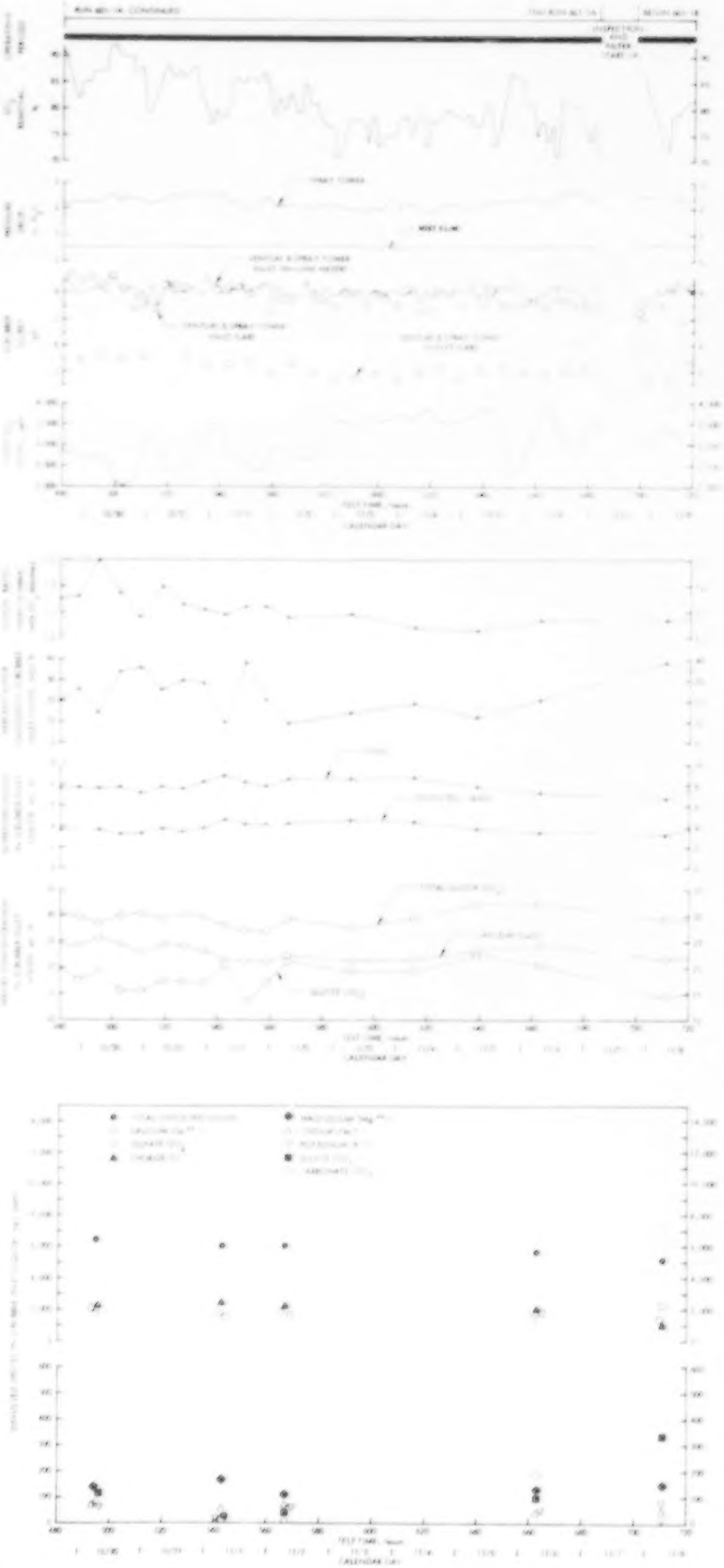
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A



Gas Rate = 25,000 acfm @ 130 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in. H_2O
E.H.T. Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 123-126 °F
Liquid Conductivity = 5,200-8,500 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 22-26 wt %

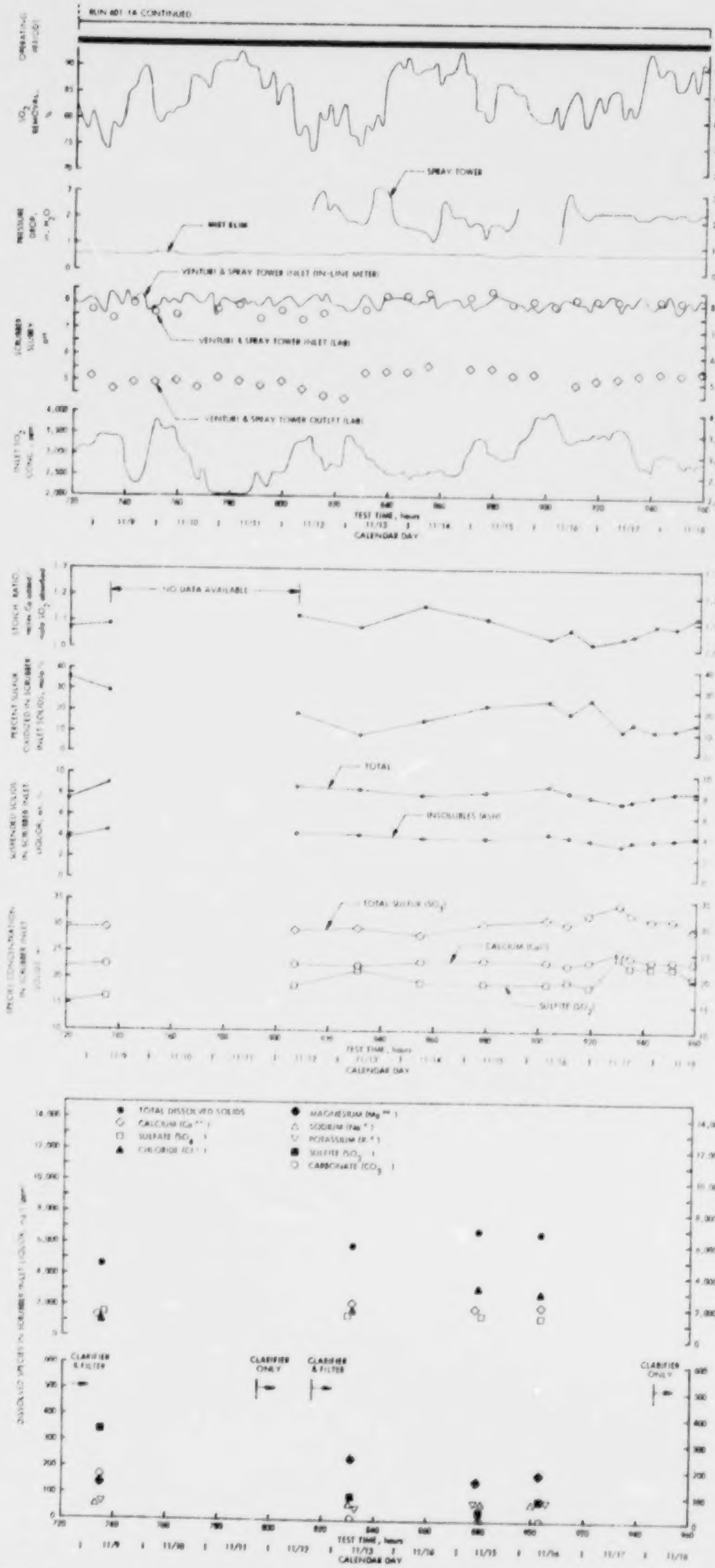
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 8.3 ft/sec
Venturi Pressure Drop = 9 in. H_2O
E.H.T. Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 123-128 °F
Liquid Conductivity = 6,000-8,400 μ mhos/cm
Discharge (Clarifier) Solids Conc. = 20-28 wt %

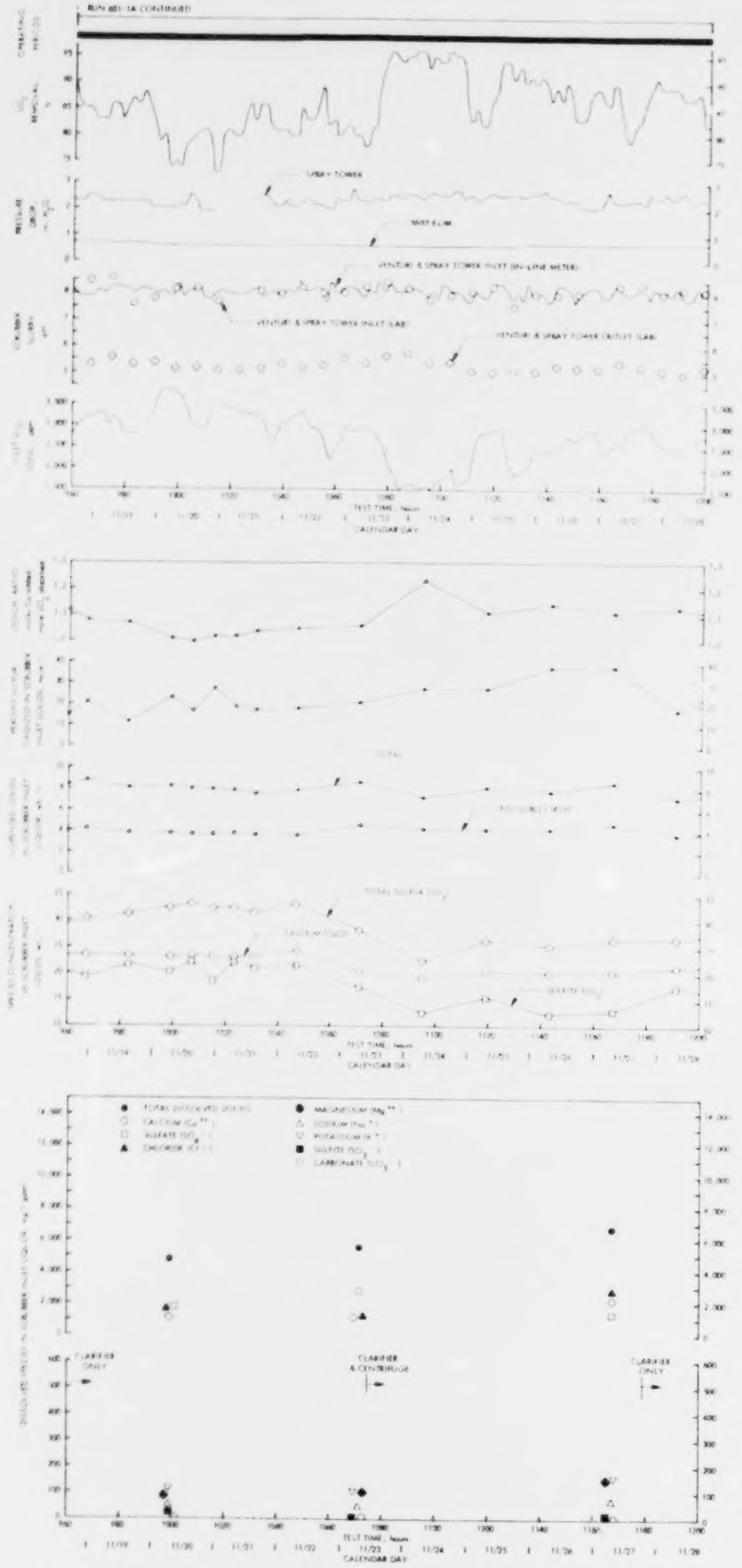
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 122-126 °F
Liquid Conductivity = 6,500-10,300 μ mhos/cm
Discharge Solids Concentration (See liquid data plot for disposal system used.)
Clarifier Only: 20-26 wt %
Clarifier & Filter: 44-51 wt %

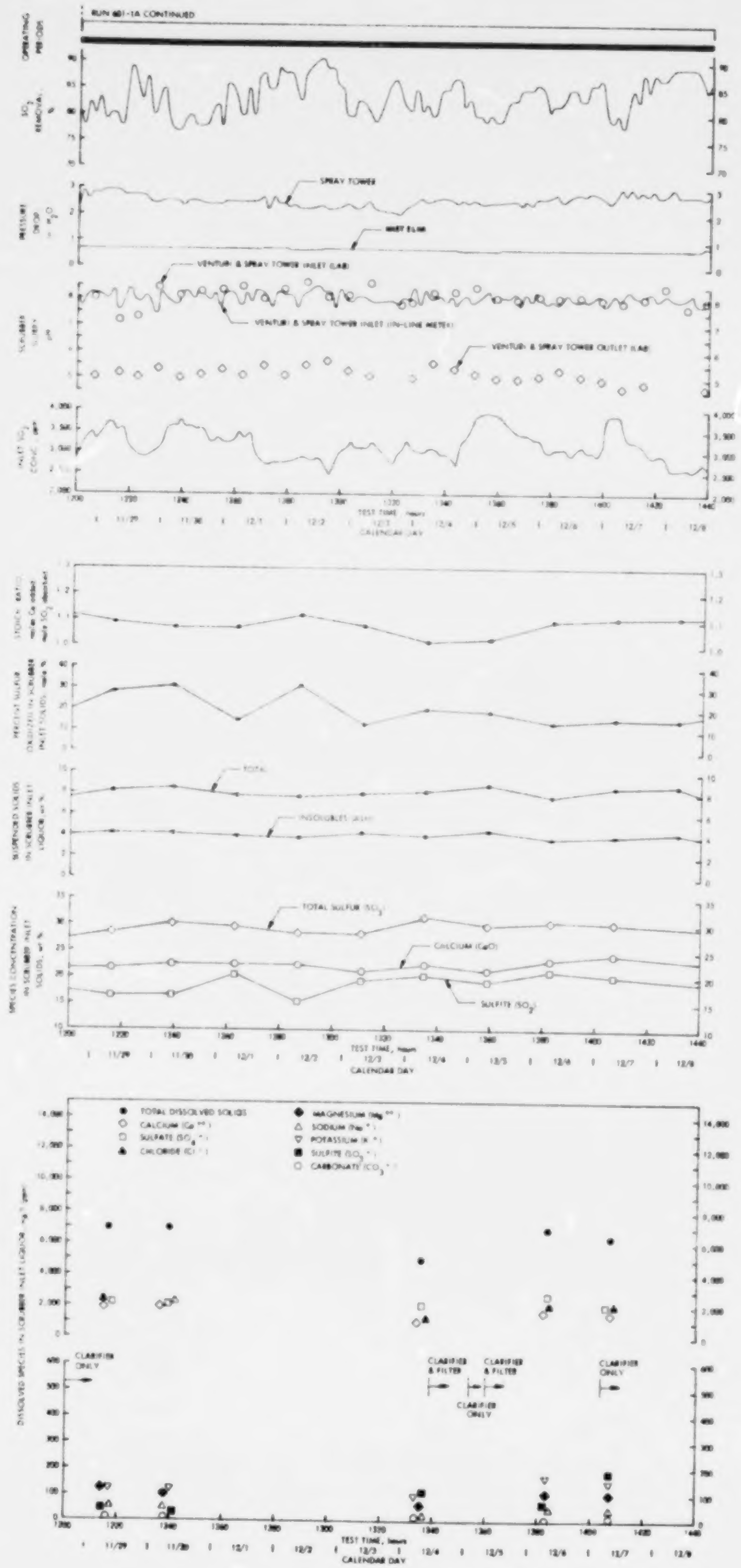
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 123-127 °F
Liquid Conductivity = 5,300-9,500 µ mhos/cm
Discharge Solids Concentration (See liquid data
plot for disposal system used.)
Clarifier Only 20-26 wt %
Clarifier & Centrifuge 54-57 wt %

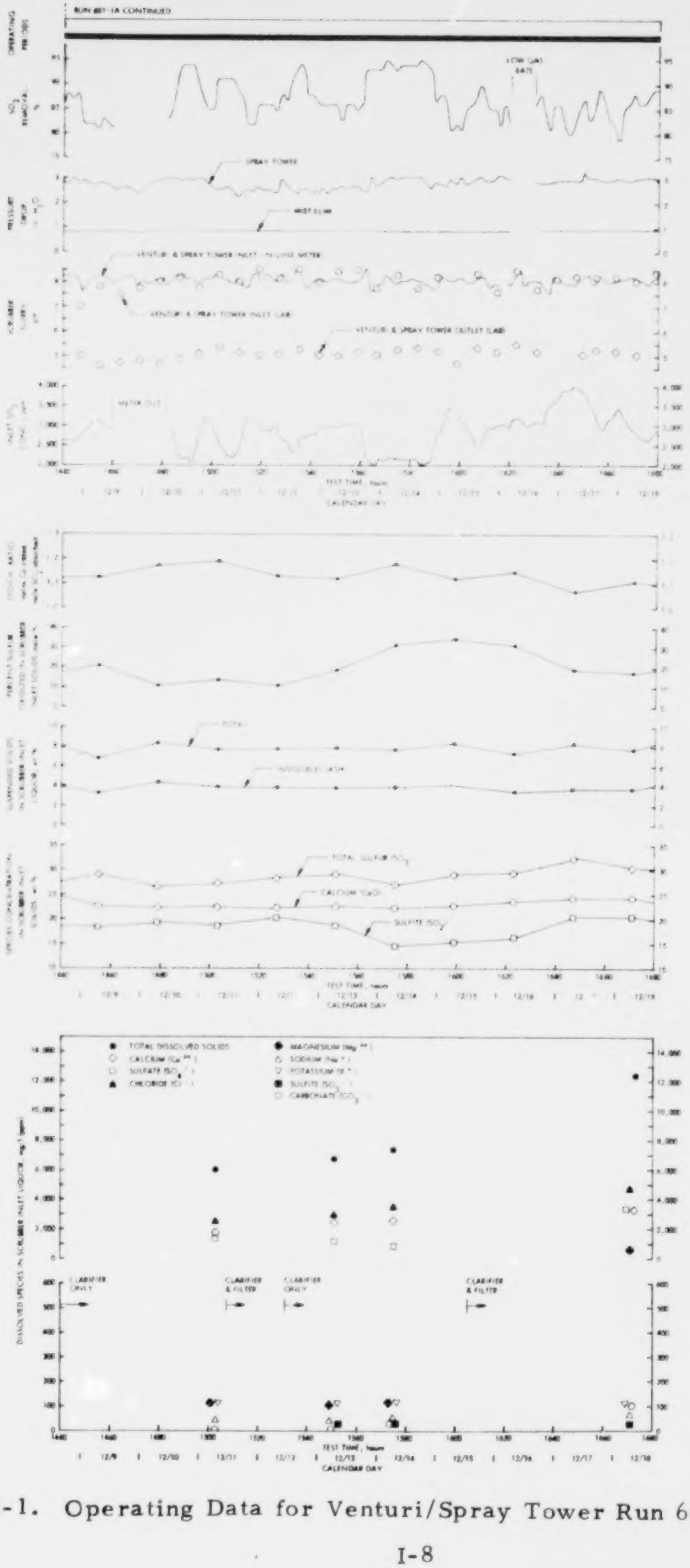
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 800 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 123-126 °F
Liquid Conductivity = 5,000-7,000 μ mhos/cm
Discharge Solids Concentration (See liquid data plot for disposal system used)
Clarifier Only: 21-27 wt %
Clarifier & Filter: 45-50 wt %

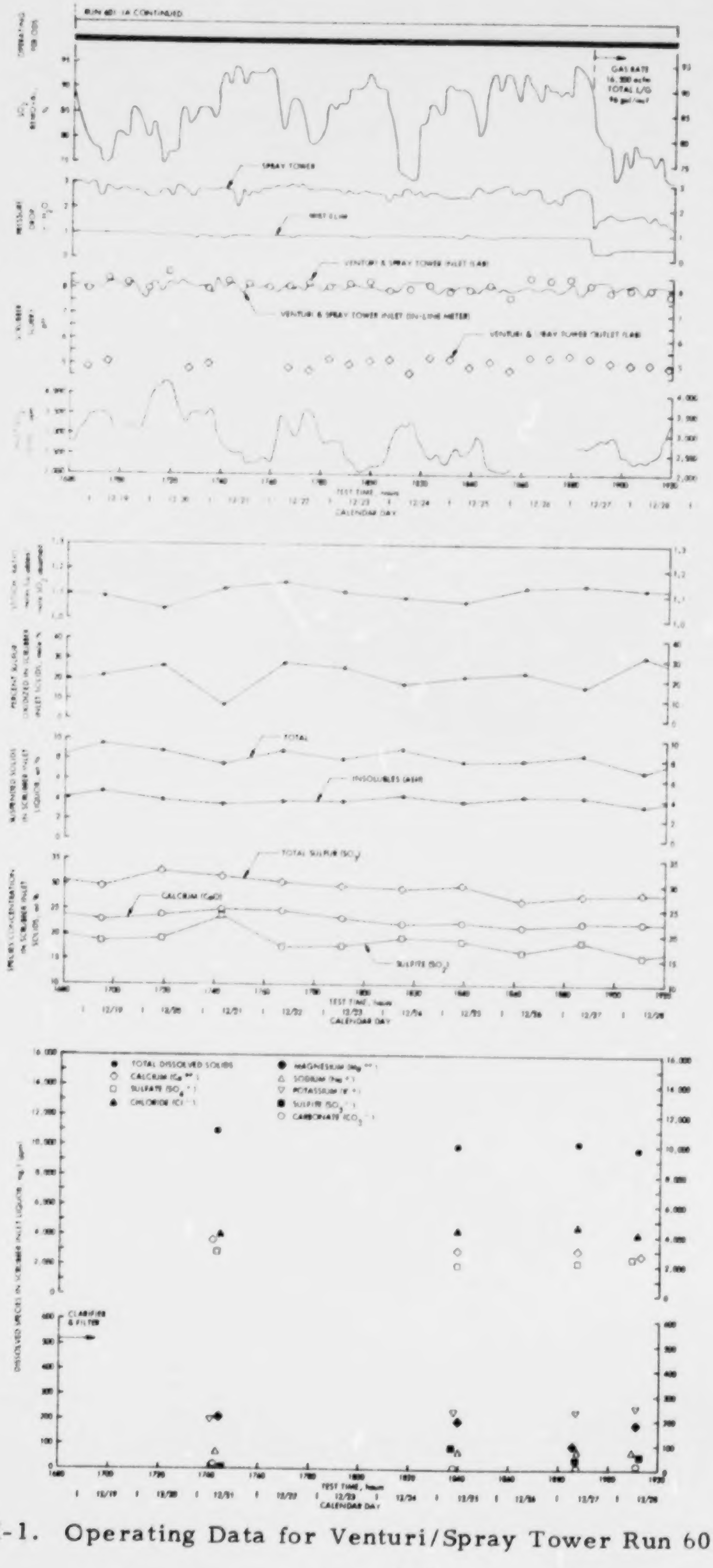
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 122-125 °F
Liquid Conductivity = 6,200-9,700 μ mhos/cm
Discharge Solids Concentration (See liquid data
    plot for disposal system used)
    Clarifier Only: 21-26 wt %
    Clarifier & Filter: 42-50 wt %

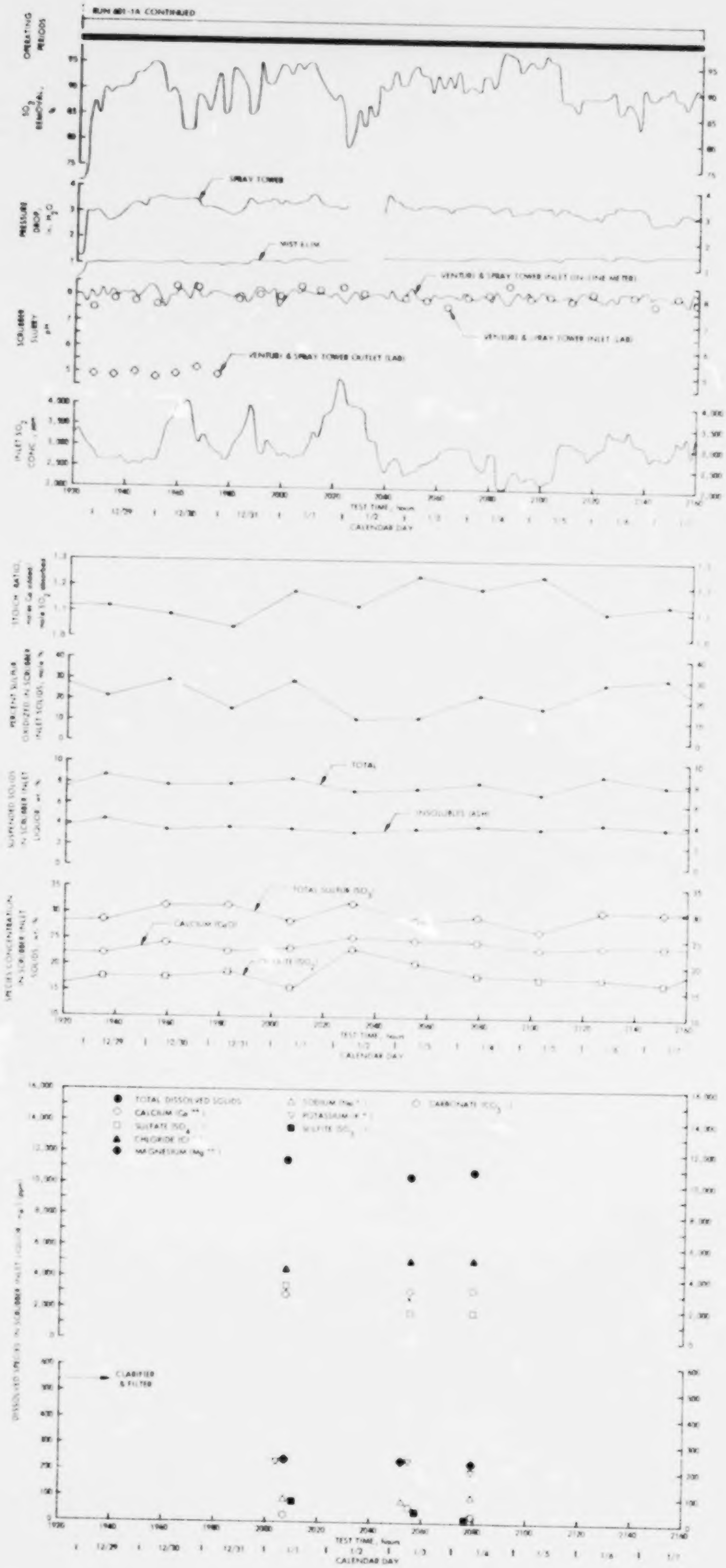
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 122-126 °F
Liquid Conductivity = 8,100-12,000 μ mhos/cm
Discharge (Clarifier & Filter) Solids
Concentration = 45-51 wt %

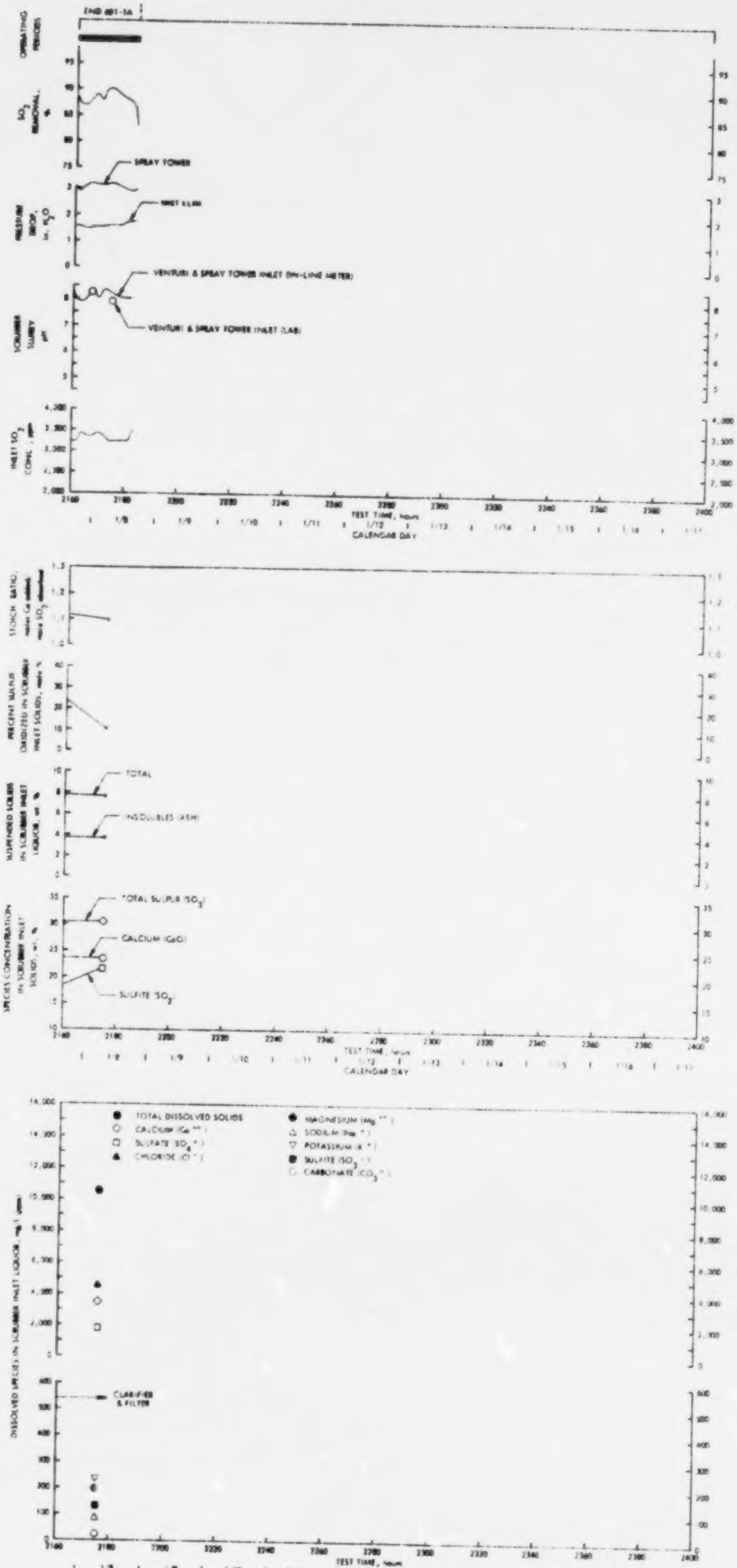
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 118-126 °F
Liquid Conductivity = 8,400-10,700 μ mhos/cm
Discharge (Clarifier & Filter) Solids
Concentration = 44-52 wt %

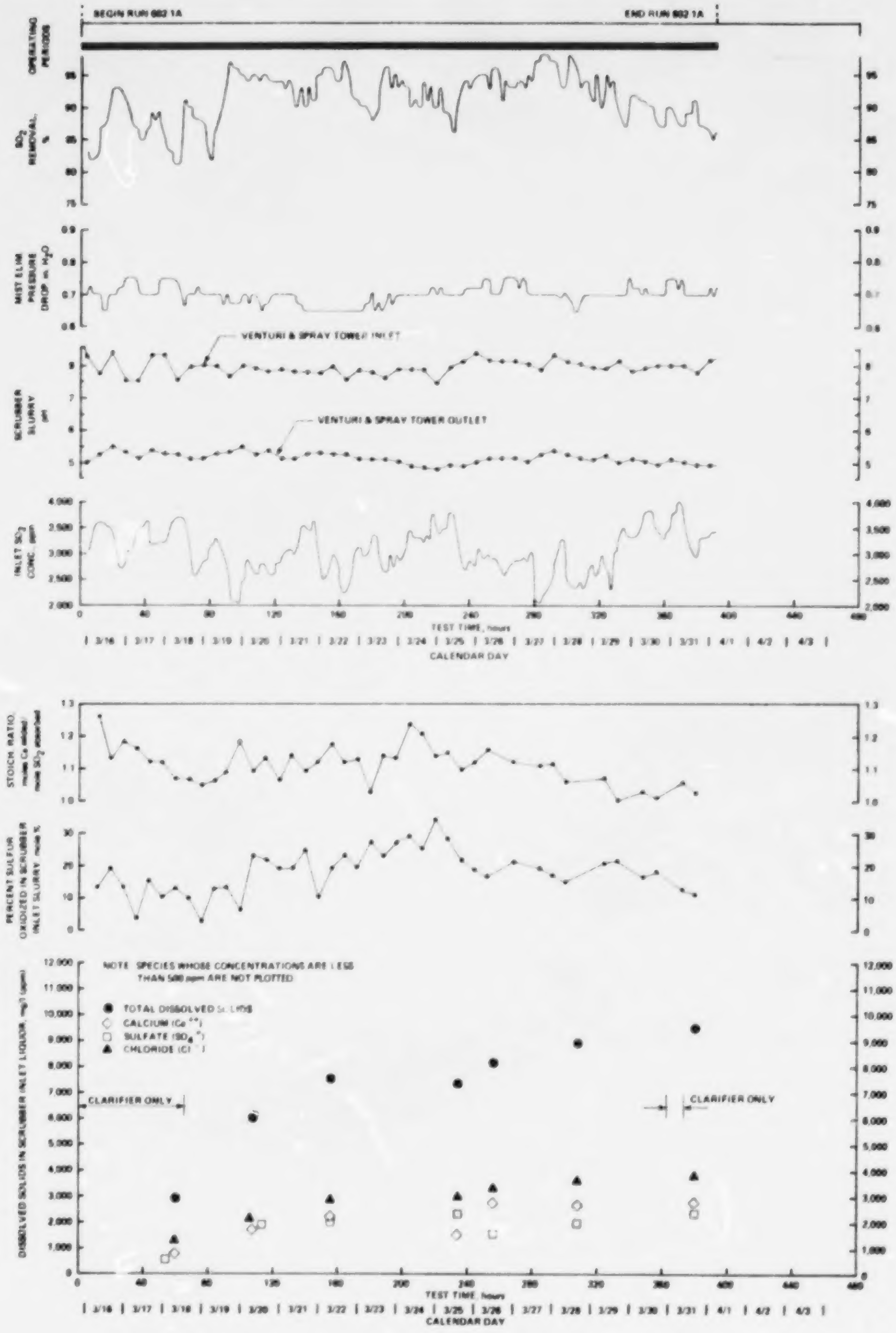
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
Venturi Pressure Drop = 9 in H_2O
Effluent Residence Time = 12 min
No. of Spray Headers = 4

Scrubber Inlet Liquor Temp. = 123-124 °F
Liquid Conductivity = 8,900 μ mhos/cm
Discharge (Clarifier & Filter) Solids
Concentration = 46 wt %

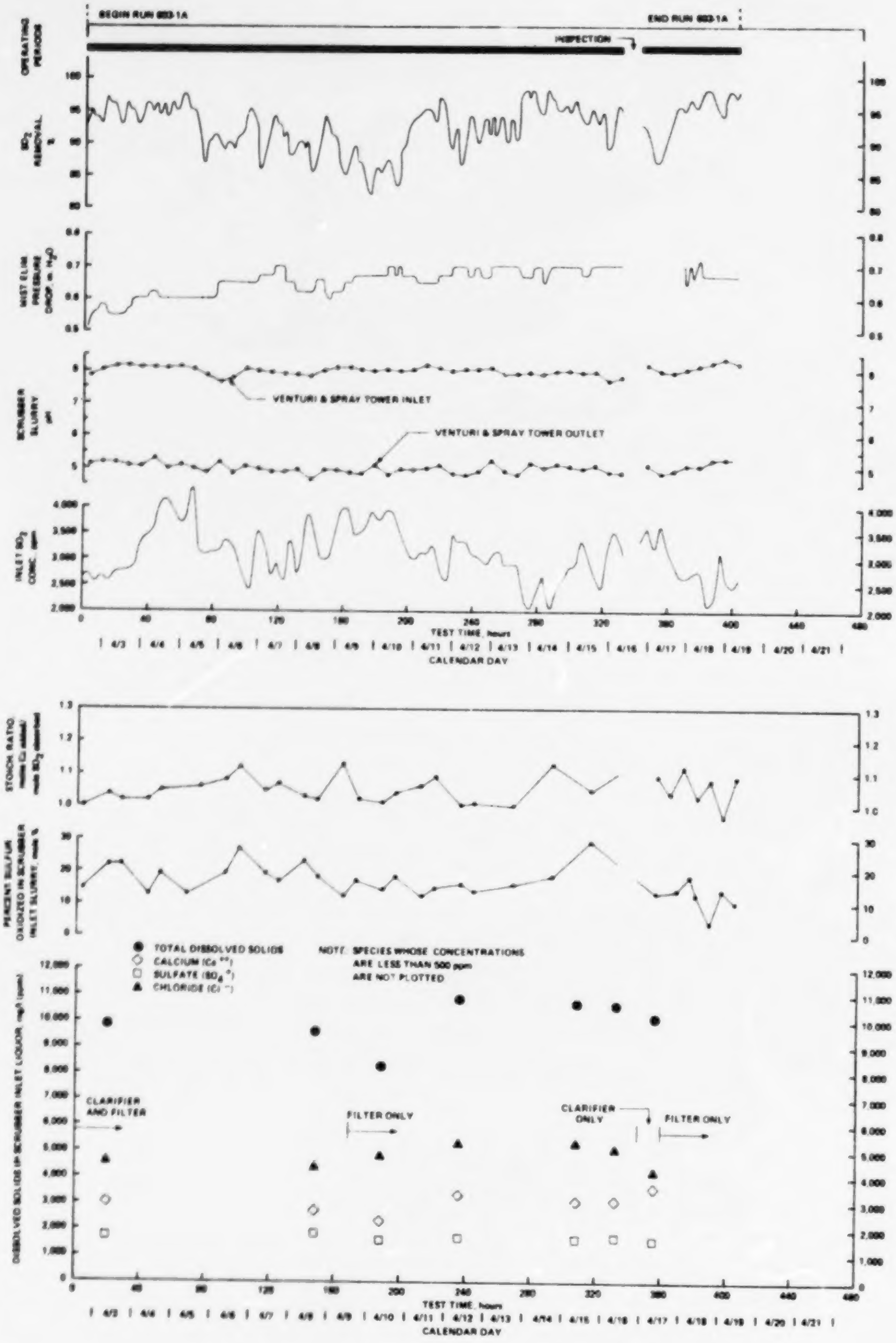
Figure I-1. Operating Data for Venturi/Spray Tower Run 601-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
EHT (Sealed) Residence Time = 12 min
No. of Spray Headers = 4

Percent Solids Recirculated = 7.5-9.5 wt %
Venturi Pressure Drop = 9 in H_2O
Total Pressure Drop, Excluding Mist Elim. = 11-12 in H_2O
Scrubber Inlet Liquor Temperature = 124-130 °F
Liquid Conductivity = 6,800-9,200 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 42-48 wt %

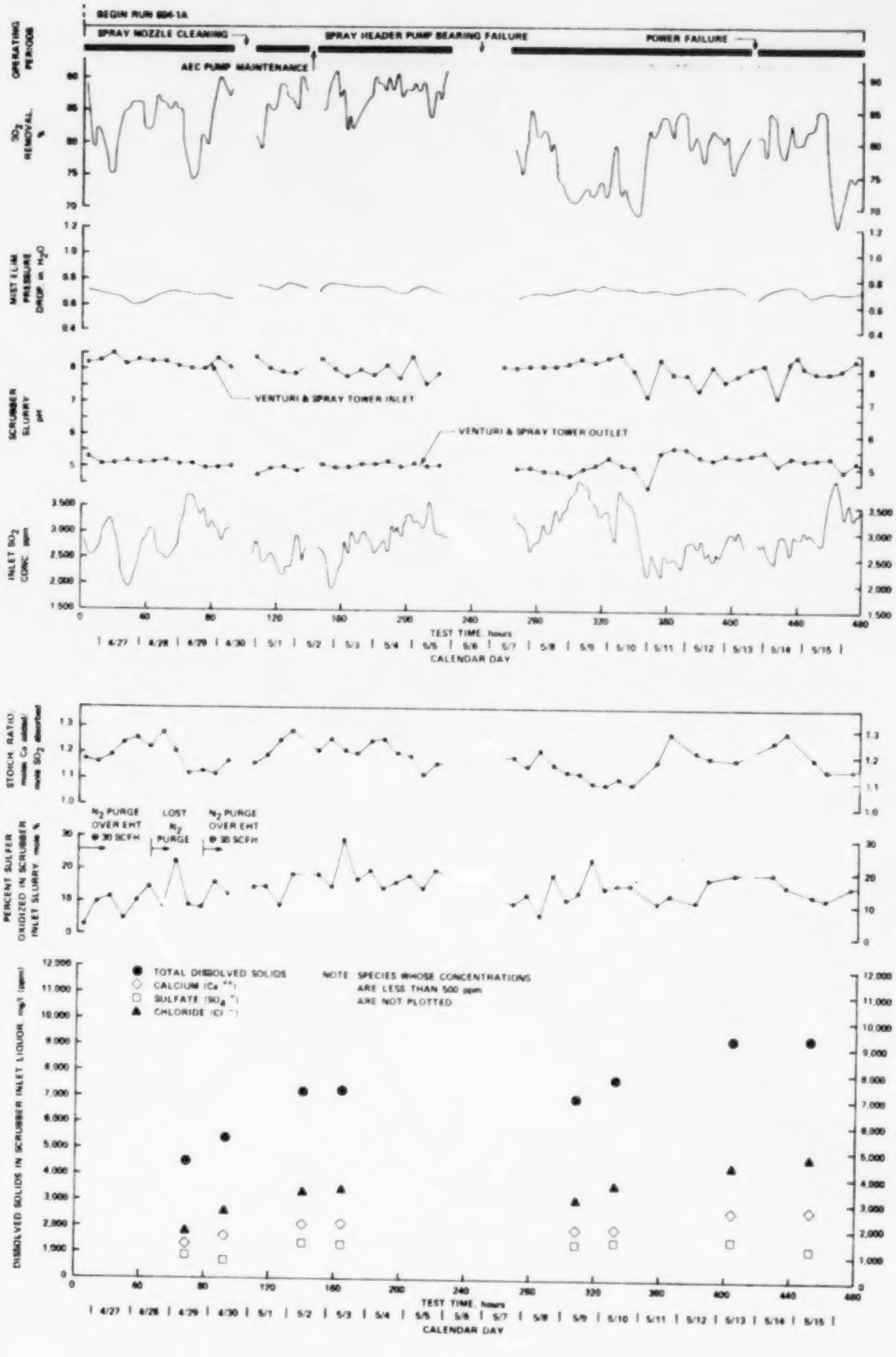
Figure I-2. Operating Data for Venturi/Spray Tower Run 602-1A



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 32 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
EHT (Sealed) Residence Time = 12 min
No. of Spray Headers = 4

Percent Solids Recirculated = 13.5-16.0
Venturi Pressure Drop = 9 in H_2O
Total Pressure Drop, Excluding Mist Elim. = 11-12 in H_2O
Scrubber Inlet Liquor Temperature = 124-130 °F
Liquid Conductivity = 7,500-11,700 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 46-54 wt %

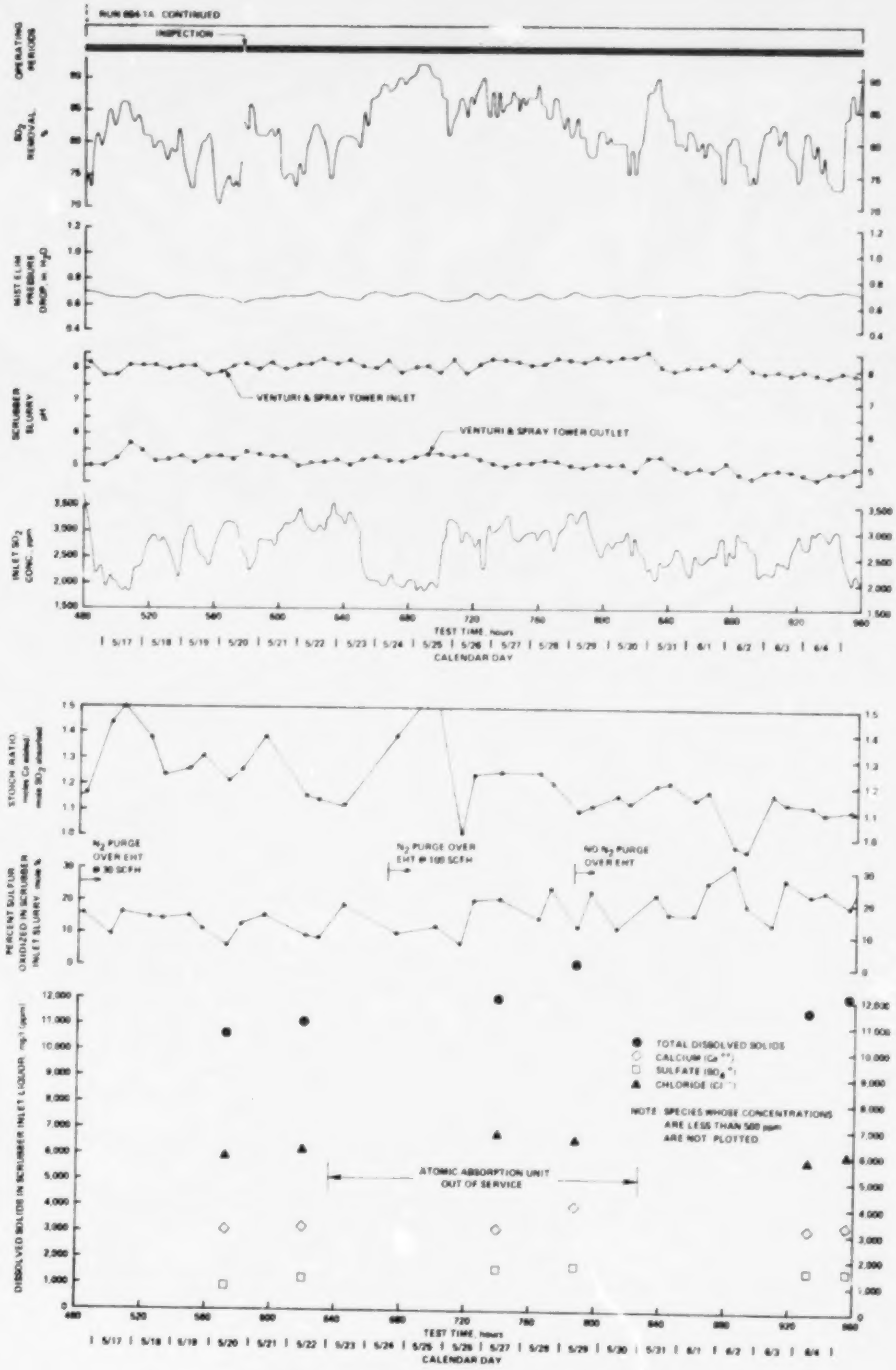
Figure I-3. Operating Data for Venturi/Spray Tower Run 603-1A



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N_2 purge) Residence
Time = 17 min

Percent Solids Recirculated = 7.5-9.0
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.3-3.9 in H_2O
Scrubber Inlet Liquor Temperature = 125-129 °F
Liquid Conductivity = 4,000-9,500 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 50-60 wt %
Lime Addition to Scrubber Downcomer

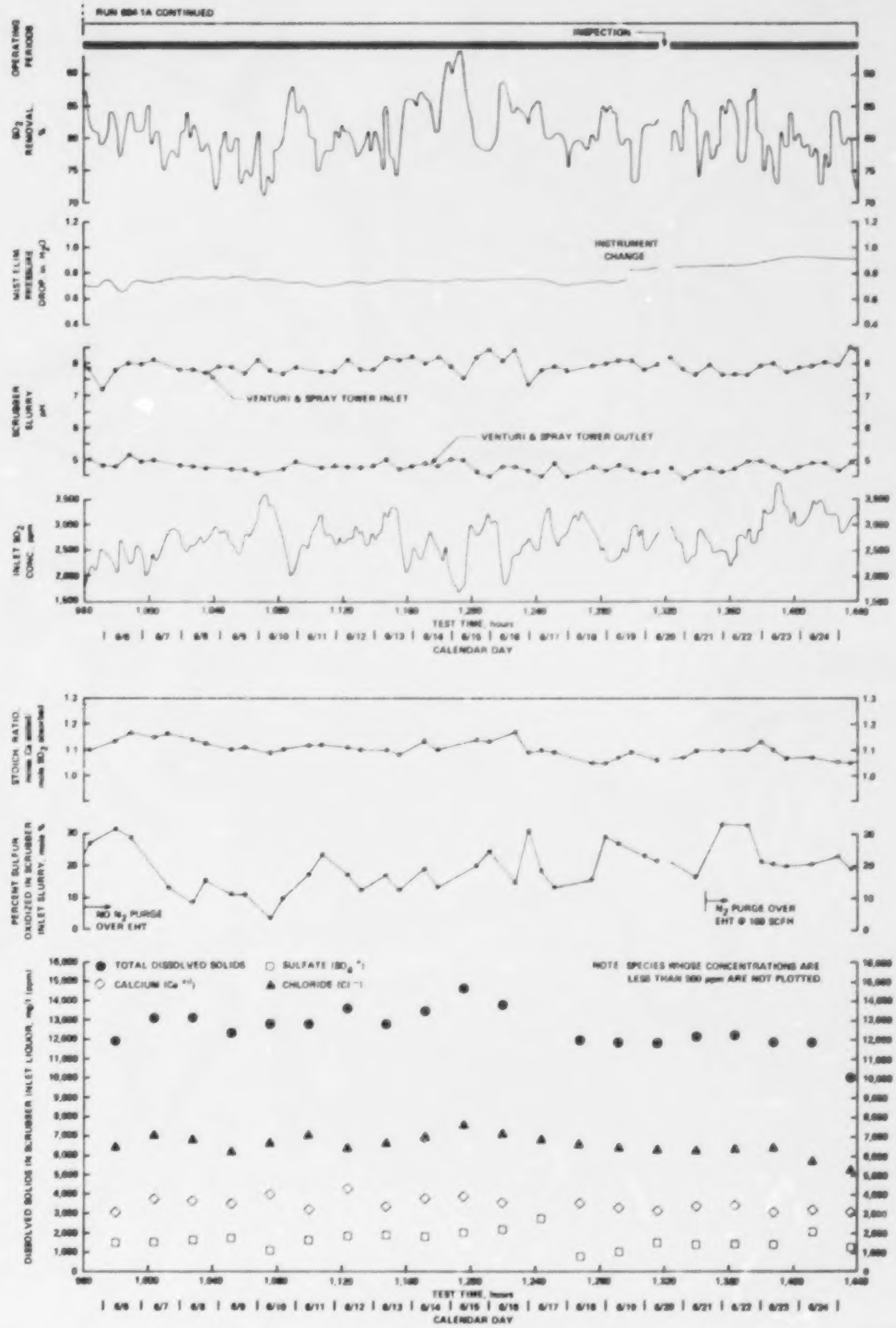
Figure I-4. Operating Data for Venturi/Spray Tower Run 604-1A



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N_2 Purge) Residence
Time = 17 min

Percent Solids Recirculated = 7.5-9.0
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.3-3.9 in H_2O
Scrubber Inlet Liquor Temperature = 126-132 °F
Liquid Conductivity = 7,400-12,000 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 50-60 wt %
Lime Addition to Scrubber Downcomer

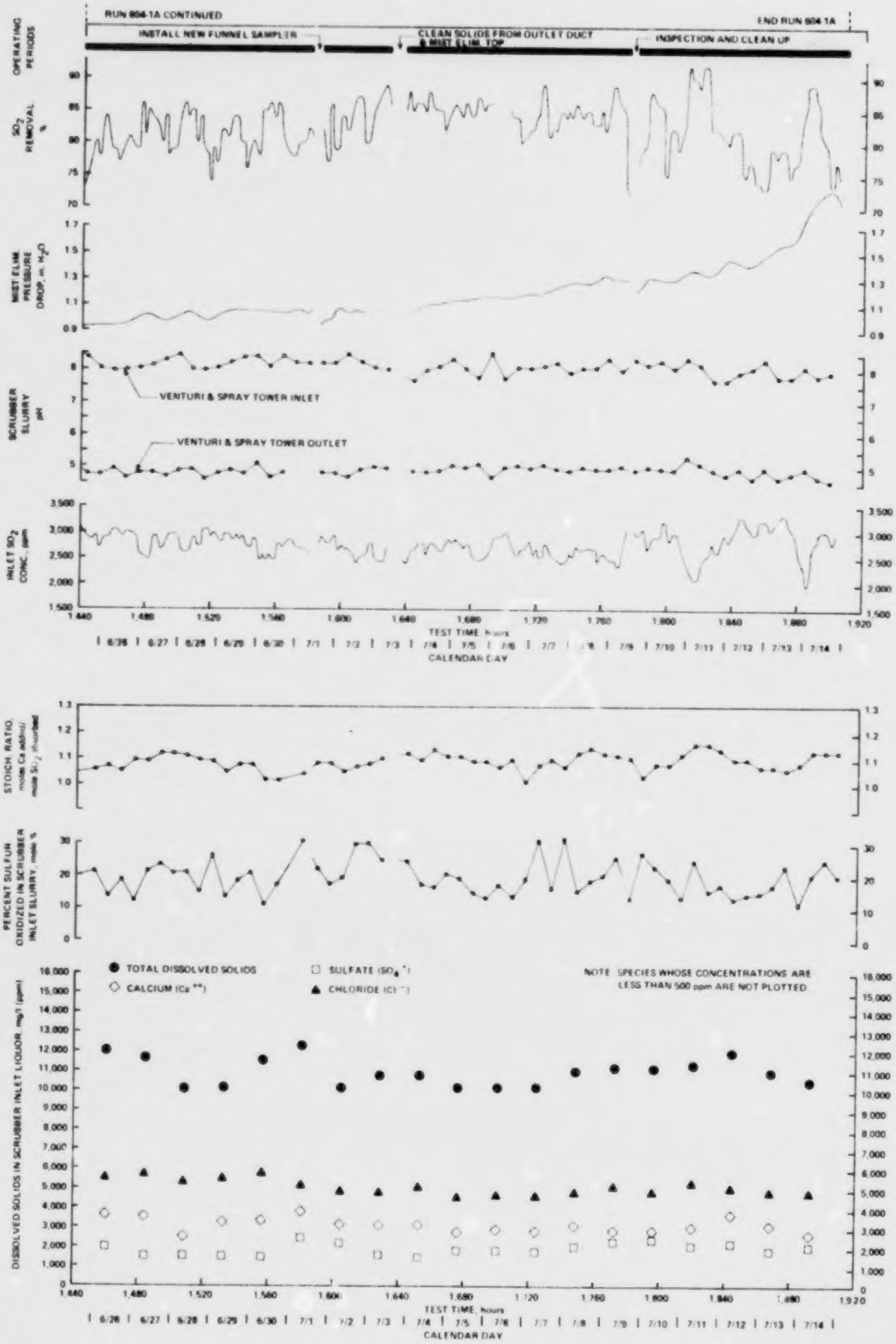
Figure I-4. Operating Data for Venturi/Spray Tower Run 604-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower L/G = 60 gal/mcf
Spray Tower Gas Velocity = 6.7 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N$_2$ Purge) Residence
Time = 17 min

Percent Solids Recirculated = 7.5-8.0 wt %
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.3-3.8 in H$_2$O
Scrubber Inlet Liquor Temperature = 126-132 °F
Liquid Conductivity = 10,000-24,000 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 50-60 wt %
Lime addition to Scrubber Downcomer

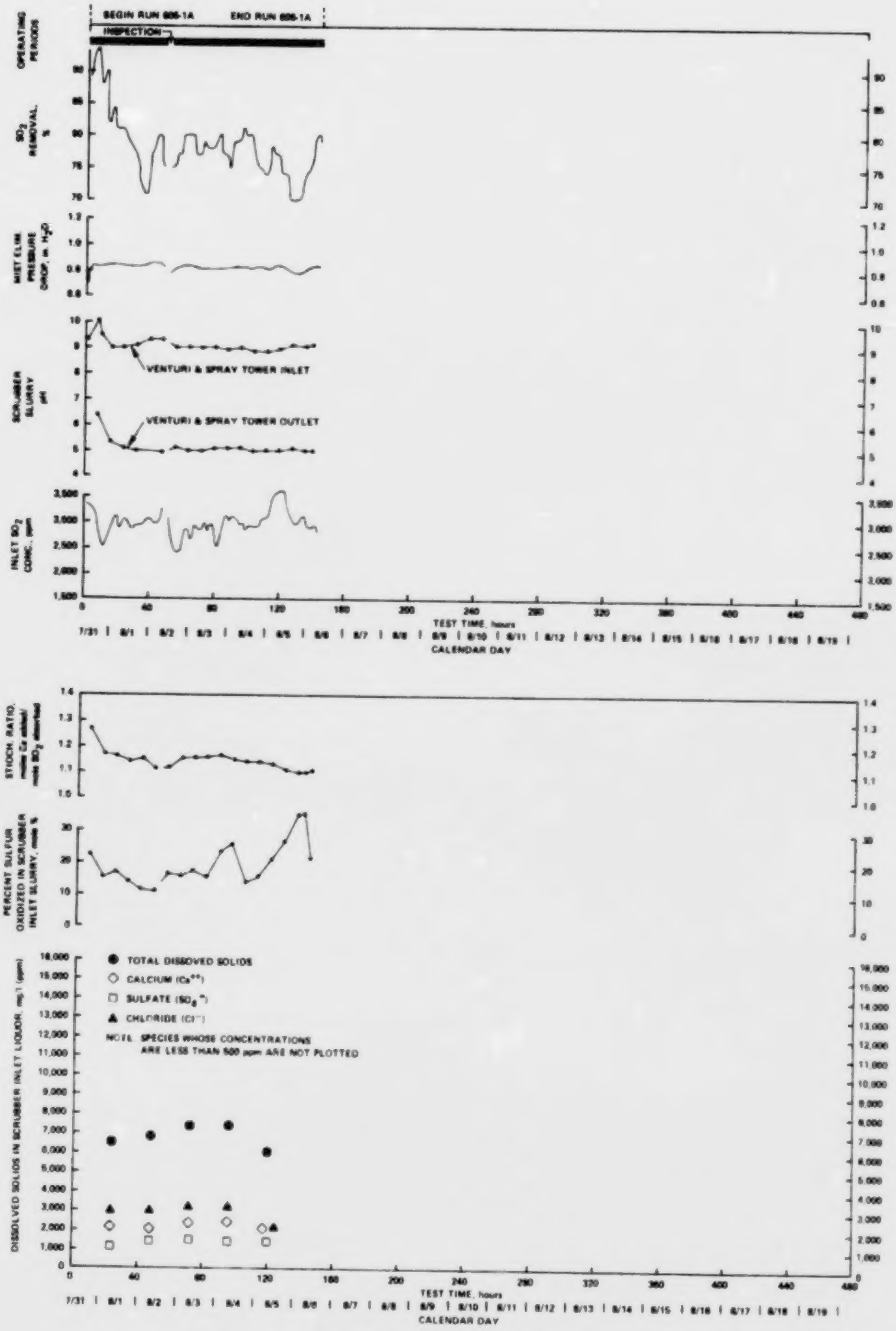
Figure I-4. Operating Data for Venturi/Spray Tower Run 604-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N_2 Purge) Residence
Time = 17 min

Percent Solids Recirculated = 7.5-9.0 wt %
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.7-4.0 in H_2O
Scrubber Inlet Liquor Temperature = 126-132 °F
Liquid Conductivity = 10,000-31,000 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 50-60 wt %
Lime addition to Scrubber Downcomer

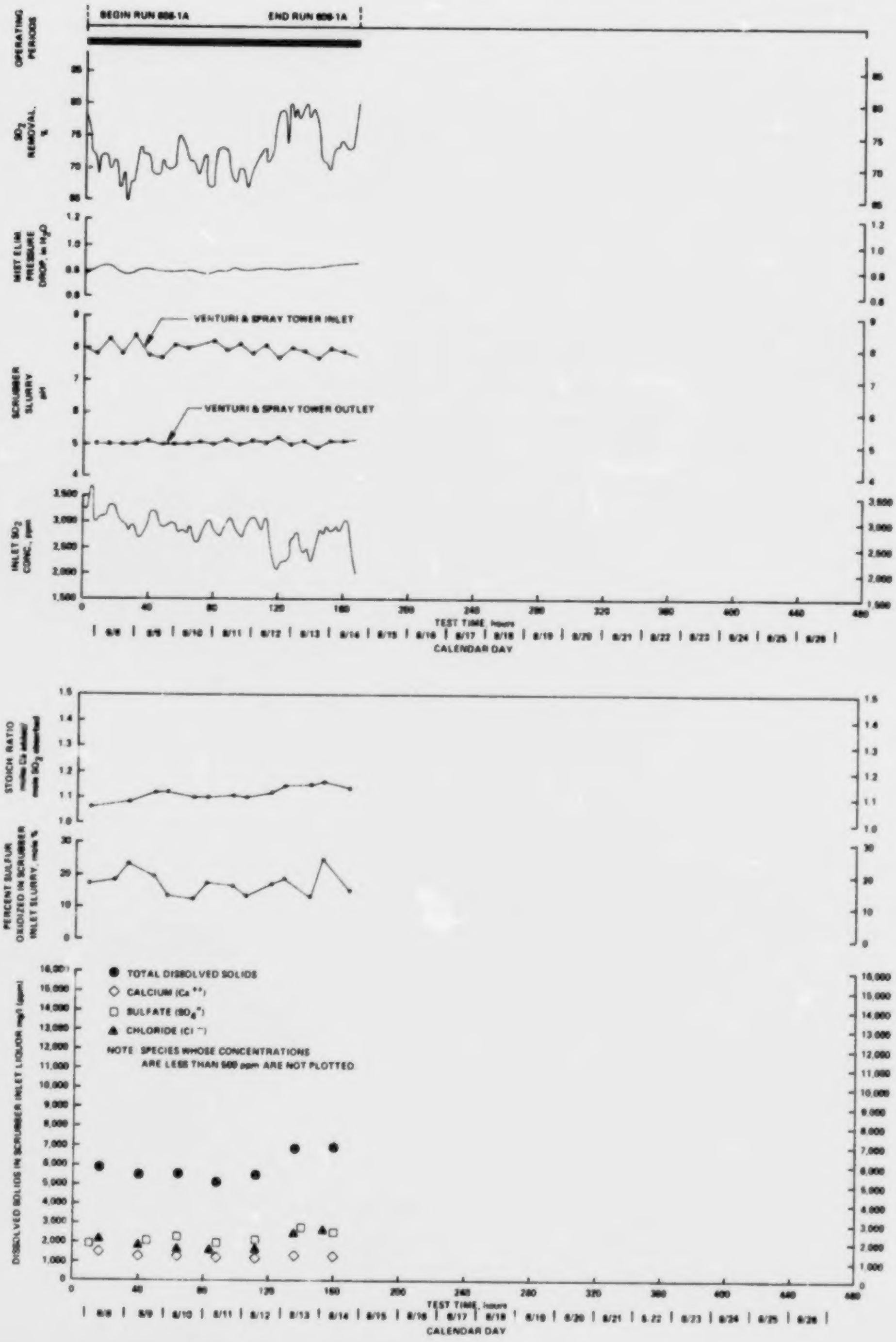
Figure I-4. Operating Data for Venturi/Spray Tower Run 604-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower Gas Velocity = 6.3 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N_2 Purge) Residence
Time = 17 min

Percent Solids Recirculated = 8.0-9.3 wt %
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.2-3.9 in H_2O
Scrubber Inlet Liquor Temperature = 128-130 °F
Liquid Conductivity = 5,600-10,000 µ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 48-52 wt %
Lime addition to Scrubber Downcomer

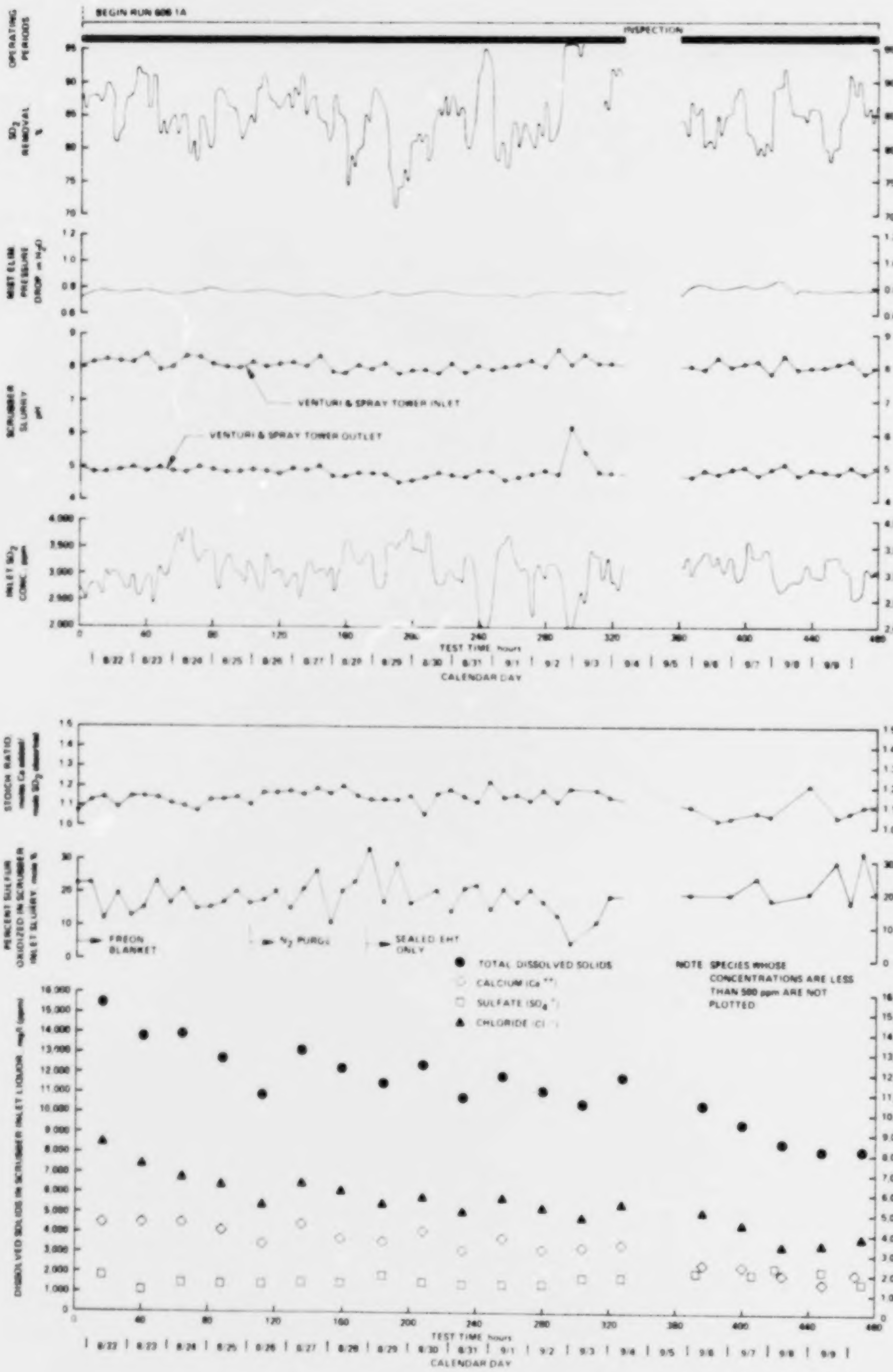
Figure I-5. Operating Data for Venturi/Spray Tower Run 605-1A



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = minimum (100 gpm)
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 5 gal/mcf
Spray Tower L/G = 64 gal/mcf
Spray Tower Gas Velocity = 6.7 ft/sec
No. of Spray Headers = 4
EHT (Sealed with N_2 Purge) Residence
Time = 17 min

Percent Solids Recirculated = 7.7-9.0 wt %
Venturi Plug Position 100% Open
Total Pressure Drop, Excluding Mist Elim. = 3.6-3.7 in H_2O
Scrubber Inlet Liquor Temperature = 130-132 °F
Liquid Conductivity = 8,100-10,000 μ mhos/cm
Discharge (Clarifier) Solids
Concentration = 18-23 wt %
Lime addition to Scrubber Downcomer

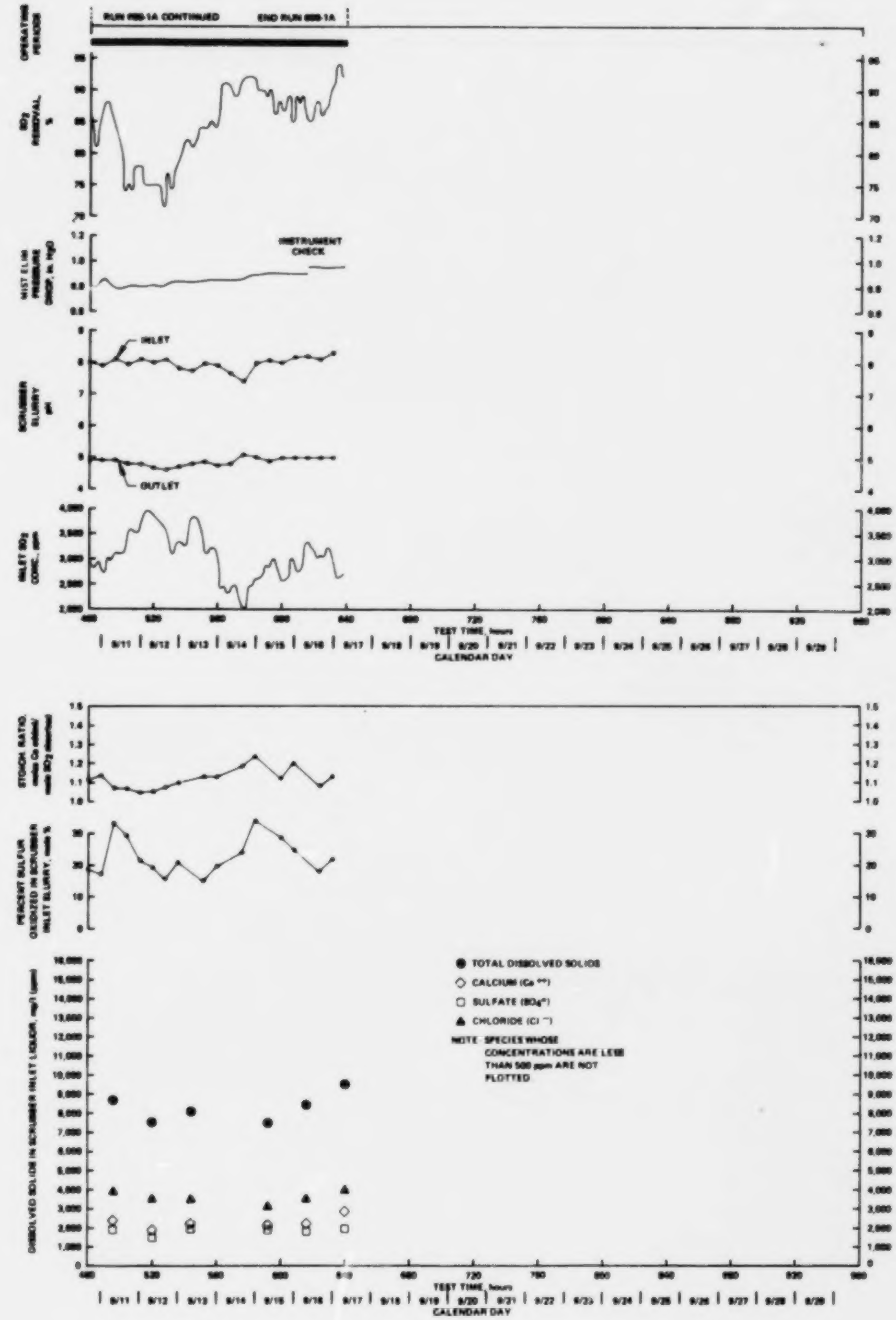
Figure I-6. Operating Data for Venturi/Spray Tower Run 606-1A



Gas Rate = 25,000 acfm 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G = 30 gal/mcf
Spray Tower Gas Velocity = 6.7 ft/sec
No. of Spray Headers = 4
EHT (Sealed) Residence
Time = 17 min

Percent Solids Recirculated = 7.7-9.4 wt %
Venturi Pressure Drop = 9 in H_2O
Total Pressure Drop, Excluding Mist Elim. = 11.5-12.2 in H_2O
Scrubber Inlet Liquor Temperature = 129-132 °F
Liquid Conductivity = 6,800-22,000 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 48-58 wt %
Lime addition to Scrubber Downcomer

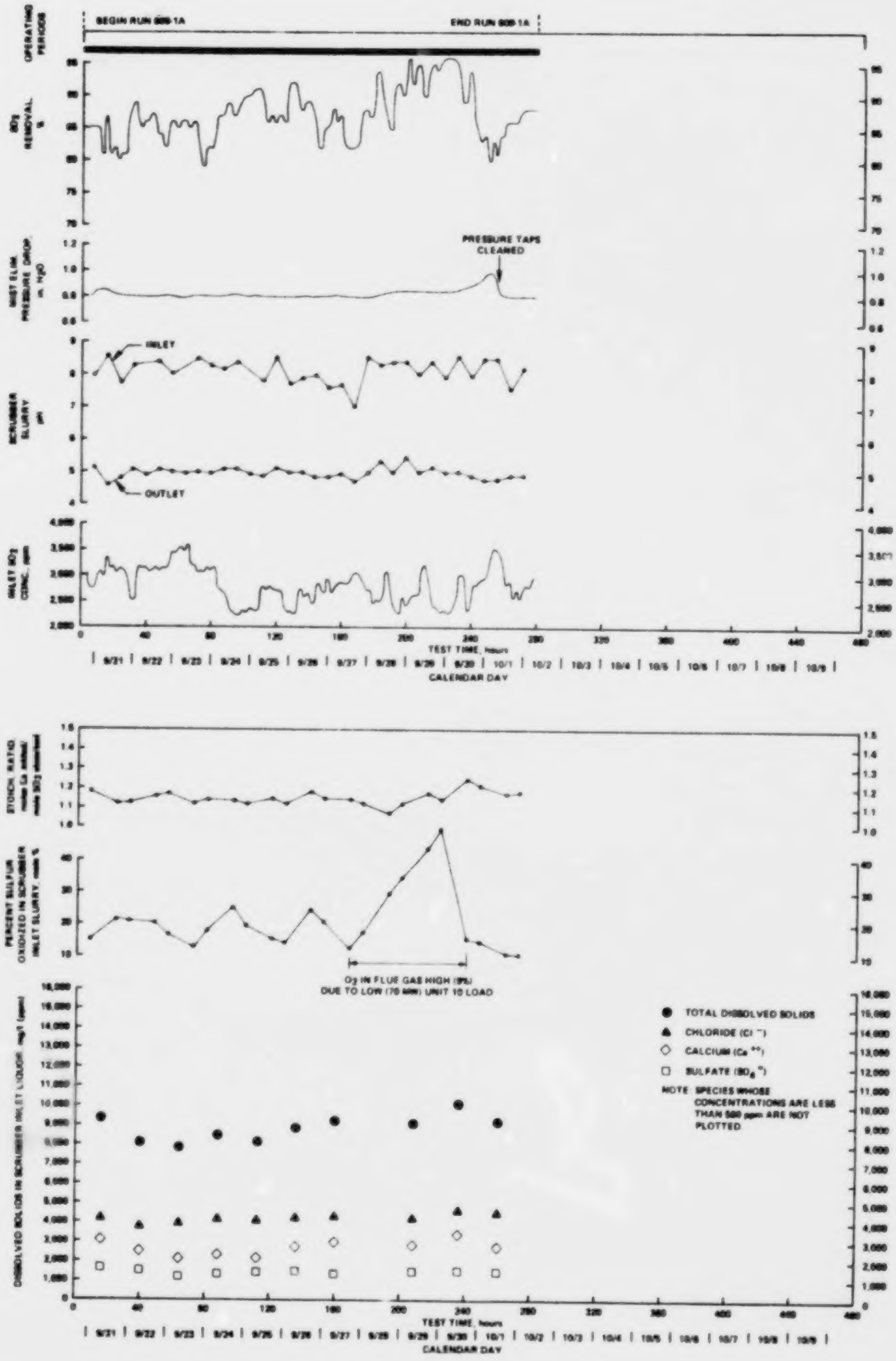
Figure I-7. Operating Data for Venturi/Spray Tower Run 608-1A



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G 30 gal/mcf
Spray Tower Gas Velocity = 6.7 ft/sec
No. of Spray Headers = 4
EHT (Sealed) Residence
Time = 12 min

Percent Solids Recirculated = 7.7-9.4 wt %
Venturi Pressure Drop = 9 in H_2O
Total Pressure Drop, Excluding Mist Elim. = 11.5-12.0 in H_2O
Scrubber Inlet Liquor Temperature = 128-132 °F
Liquid Conductivity = 7,100-9,200 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 48-58 wt %
Lime addition to Scrubber Downcomer

Figure I-7. Operating Data for Venturi/Spray Tower Run 608-1A (continued)



Gas Rate = 25,000 acfm @ 330 °F
Liquor Rate to Venturi = 600 gpm
Liquor Rate to Spray Tower = 1200 gpm
Venturi L/G 30 gal/mcf
Spray Tower Gas Velocity =6.7 ft/sec
No. of Spray Headers = 4
EHT (Sealed) Residence
Time = 24 min

Percent Solids Recirculated = 7.0-9.0 wt %
Venturi Pressure Drop = 9 in H_2O
Total Pressure Drop, Excluding Mist Elim. = 11.0-11.85 in H_2O
Scrubber Inlet Liquor Temperature = 125-128 °F
Liquid Conductivity =9,000-13,000 μ mhos/cm
Discharge (Clarifier and Filter) Solids
Concentration = 47-52 wt %
Lime addition to Scrubber Downcomer

Figure I-8. Operating Data for Venturi/Spray Tower Run 609-1A

Appendix J

FIRST TVA INTERIM REPORT OF CORROSION STUDIES: EPA ALKALI SCRUBBING TEST FACILITY

by

G. L. Crow
H. R. Horsman

October 1973

NOTE: The Hydro-Filter scrubber has been renamed the "Marble-Bed Absorber". It is referred to, however, as "Hydro-Filter" in this appendix.

EPA ALKALI-SCRUBBING TEST FACILITY--SHAWNEE POWER PLANT

Interim Report of Corrosion Studies

Identification and solution of corrosion and erosion problems associated with construction materials are important goals in a program for the design and evaluation of limestone - wet-process systems for removing sulfur dioxide from stack gas at coal-fired power plants. The program at the Shawnee Power Plant is a cooperative effort among the Environmental Protection Agency (EPA), Bechtel Corporation, and TVA.

Earlier corrosion tests made in pilot-plant studies by the Process Engineering Branch* of limestone - wet-scrubbing systems at Colbert Power Plant showed that some materials of construction were durable while others were severely attacked under plant operating conditions (Process Engineering Branch reports--Sept. 1971, Dec. 1971, July 1972, and Aug. 1972).

At the request of the EPA in 1972, the Process Engineering Branch of TVA started corrosion tests of 17 alloys and 7 nonmetals at 21 strategic locations in three parallel scrubber systems at the Shawnee Power Plant. The systems were the venturi, the Turbulent Contact Absorber (TCA), and the Hydro-Filter; each of these had the capacity to handle 30,000 acfm of gas.

After the systems had been operated from 1700 to 2200 hours, the results of corrosion tests and of plant inspections showed that greatest corrosion had occurred in areas such as inlet ducts and venturi where wetted gas or gas and slurry flowed at high velocity. Typically, the stack gas contained 0.3% SO_2 and 3 to 5 grains of fly ash per cubic foot. Deposits of solids, such as limestone and fly ash, prevented erosion but caused corrosion of the concentration cell type in some areas. The most resistant alloys tested were Hastelloy C-276, Inconel 625, Incoloy 825, Carpenter 20 Cb-3, and Type 316L stainless steel. Hastelloy C-276 was the most durable and also the most expensive; Type 316L stainless steel ranks fifth in durability but eleventh in cost of the alloys tested. Rubbers, such as butyl, natural, and neoprene, showed good resistance. With some exceptions, units of plant equipment made of Type 316L stainless steel or lined with neoprene or with polyester inert flake material were durable. Testing work is being continued.

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*Process Engineering Branch of the Tennessee Valley Authority.

Program and Plans

Program: The limestone - wet-scrubbing program for sulfur dioxide removal at Shawnee is funded and directed by EPA. The Bechtel Corporation designed the plant facility and TVA built it. TVA is operating the plant under a test program developed and directed by Bechtel. Evaluation of construction materials by exposure of test specimens at strategic locations and by inspection of the plant equipment is an important goal in the program.

Plans: Responsibility for conducting the evaluation program at Shawnee was assigned TVA in March 1972. /Report to Air Pollution Control Office, EPA (Contract No. PH 22-68-67, June 28, 1968), by Bechtel Corporation (March 2, 1972)./ The Process Engineering Branch of the Division of Chemical Development was given this task. /Informal memorandums--H. W. Elder to R. D. Young (April 5, 1972) and Ronald D. Young to H. W. Elder (April 7, 1972)./ This work includes procuring test materials, making test specimens, fabricating suspension equipment for spools and racks of specimens in the plants, and reporting test results. Also included are periodic inspection and evaluations of plant equipment for corrosion and wear.

Bechtel Corporation specified 20 materials of construction that consisted of 17 alloys and 3 nonmetals to be tested at 24 designated locations in the three plants. /Material List of Corrosion Coupon Test Rack (2/15/72) and Drawings SK-M-102 through 109 and SK-M-111 (Job 6955), Bechtel Corporation./

Plant Facility: Figure 1 is a view of the plant showing the three parallel scrubbing systems--the venturi, the TCA, and the Hydro-Filter.

Power plant stack gas at an average temperature of 320°F (300°-350°F) flows through a 40-inch duct to a system where it is sprayed for humidification and for cooling. It then passes through limestone slurry in a particular type of test scrubber for sulfur dioxide removal. Afterward, it is freed of mist in a separator, reheated to between 235° and 265°F to vaporize mist and eliminate a plume, and discharged through a fan and duct to the atmosphere. Scrubber effluent is clarified to remove solids which are discarded and the liquor is then recirculated.

Some features common to all the systems are described below. A 40-inch duct is used to carry the stack gas at 320°F from the No. 10 boiler of the power plant to a test system; each duct is made of 10-gage carbon steel, ASTM A-283, and is insulated except at flanged joints. The 40-inch duct connects to another gas duct made of Type 316L stainless steel. This duct is equipped with two sets of spray nozzles (the first for humidifying and the second for cooling the gas) and an air-operated soot blower.

Downstream from each sulfur dioxide absorber and mist eliminator unit there are a stainless steel duct, a refractory-lined reheater fired with fuel oil, an induced-draft fan of stainless steel, and a stack of stainless steel. For liquor handling there are a slurry recirculation tank, a scrubber effluent tank, and a liquor clarification system. The effluent hold tank and a clarifier tank are made of carbon steel A-283 and coated inside with Flakeline 103 which is a Bisphenol polyester resin-fiber glass coating manufactured by the Ceilcote Company. The recirculation tank, clarified water storage tank, and reslurry tank are made of carbon steel and lined with neoprene.

Distinguishing features of the systems are as follows. In the venturi scrubber system shown in Figure 2, the gas is scrubbed in a venturi unit made of Type 316 stainless steel and then passed through a neoprene-lined spray tower (afterscrubber) with a chevron-type separator in the top for mist recovery. In the TCA system, shown in Figure 3, gas is scrubbed in a mobile bed of wetted balls, and the mist is removed in a Koch FlexiTray and chevron-type separator in a tower lined with neoprene. In the Hydro-Filter system shown in Figure 4, gas is scrubbed in a flooded bed of marbles, and the mist is removed in a chevron-type mist separator in a neoprene-lined scrubber tower.

Preparations for Corrosion Tests

With Bechtel's approval, several improvements were made in plans for the design, preparation, and installation of test specimens. Nonmetallic materials added to the test materials list included Qua-Corr, a fiber glass-reinforced furan resin, and the rubbers--butyl, natural, and neoprene. Stressed specimens of five alloys were also added to detect stress-corrosion cracking under plant operating conditions.

Disks: Disk-type specimens, 2 inches in diameter, were prepared from the 17 metals. A weld was made (according to manufacturer's recommendations) across the diameter, and after being welded, the metal was cooled slowly in still air to simulate conditions of constructing or repairing large equipment. Whenever it was available, metal stock of 1/8-inch minimum thickness was used, and the surfaces were machined smooth after the welding. Some alloys available only in thinner gages could not be machined, so the weld beads were smoothed by grinding. A hole, 23/64 inch in diameter, was drilled in the center of each disk for mounting.

Three nonmetallic materials, Bondstrand 4000, Flakeline 200, and Transite, were also prepared as 2-inch disks and mounted on spools along with the metal disks. Flakeline 200, a coating material, was applied on mild steel disks by the manufacturer. Bondstrand 4000 and Transite are self-supporting materials and are obtained in sheet form for disk preparation.

Stressed: A strip approximately 1/8 by 1 by 5-1/2 inches was welded at midlength, machined to smooth all the surfaces, and formed into a U shape. One-half-inch holes were drilled in each end of the strip to accommodate a bolt (Type 316 stainless steel, 1/4 inch) fitted with Teflon insulators for applying static stress in the specimen.

Coated: Because of their large sizes of approximately 4-1/2 by 4-1/2 inches, the plate specimens of Qua-Corr plastic and the butyl, natural, and neoprene rubbers were mounted on a separate rack. Qua-Corr is a self-supporting material; the rubbers were applied on mild steel specimens by the manufacturer. The durometer "A" hardness values of the rubber-coated specimens as received were as follows: natural, 34-37; butyl, 54-56; and neoprene, 64-65.

Mounts and Suspensions: Spools and racks for mounting the test specimens and also the suspension equipment for installing them in the plants were constructed mainly of Type 316 stainless steel. Bolts and nuts were annealed to remove stresses caused by cold-working in threading operations. To prevent loss of fasteners through vibration of equipment, two nuts were locked by forcing them together.

At some test locations inside plant equipment, brackets were attached as permanent fixtures by welding, and then the spools of specimens were bolted to them. In other locations, spools were fastened to existing pipes by the use of band-type clamps. In a tank, spools were suspended by means of a 1/8-inch strip or a 3-inch pipe that was bolted to the top. Sleeves (3/8-inch wall by 6 inches long) of soft butyl rubber were placed around the 3-inch specimen support pipe as cushions to prevent abrasion damage to the Flakeline coating or neoprene lining on a tank wall. No specimens were installed inside pipelines or fittings.

Figure 5 shows the three types of assemblies used for mounting the corrosion test specimens. These were:

(A) Stressed--with 5 U bends

(B) Rack--with three rubber-coated plates and one plastic plate

(C) Spool--with 20 disks consisting of 17 alloys and 3 nonmetals

A Teflon sleeve was used to insulate the specimens from the supporting stainless steel bolt, and Teflon spacers or washers were used to prevent contact of the dissimilar materials.

Figure 6 shows prepared specimens and support equipment before shipment from the Office of Agricultural and Chemical Development (OACD) to Shawnee in August 1972. A few racks of specimens are shown attached to 3-inch pipe and to 1/8-inch-thick strap.

Test Exposures, Conditions, and Procedures

Test specimens of materials listed in Tables I, II, and III were installed in the three plant systems in August 1972. Table IV gives the analysis of each of the 17 metals tested. Specimens were exposed at test locations identified by series 1000, 2000, and 3000 as shown in Figures 2, 3, and 4; however, specimens (1004-6) were omitted in the venturi after-scrubber tower that was to be modified. All specimens remained in the scrubber systems from August 12, 1972, to February 3, 1973, except those in the TCA system which were temporarily removed for preliminary evaluation in November 1972.

Plant Operation: Usually, one system was operated at a time, although all three could be operated simultaneously. Operating hours in the exposure period are shown below.

System	Hours	
	Idle	Operated
Venturi	2340	1840
Turbulent Contact Absorber	2535	1667
Hydro-Filter[a]	1950	2203

[a] Also called marble bed.

Plant Process Materials and Deposits: Typical compositions of inlet and outlet gas at the scrubber systems are tabulated below.

Component	Stack gas	Scrubbed gas
SO_2, %	0.3	0.05-0.2
CO_2, %	13	12
N_2, %	74	69
O_2, %	4.5	4
H_2O, %	8	15
Fly ash, gr/std ft^3	3-5	0.02

Temperature of the inlet stack gas from unit 10 boiler averaged 320°F (300°-350°F) and that of the exhaust gas after being reheated was 235° to 265°F.

Ranges in properties of liquor in the different tanks of the three scrubber systems are summarized below.

	Liquor in tanks		
	Recycle	Effluent	Clarifier
Temperature, °F	70-125	75-130	70-100
Solids, % by weight	4-15	4-10	0-30
pH	5.3-6.4	5.6-6.8	6.0-7.6
Composition, % by weight			
$CaSO_4 \cdot 2H_2O$	1.0-3.0	1.0-2.0	0-6
$CaSO_3 \cdot 1/2H_2O$	1.5-5.0	1.5-3.5	0-10
Unreacted limestone plus fly ash	1.5-7.0	1.5-4.5	0-15
Water	85-96	90-96	70-100

Table V shows analyses of deposits from the three systems in the plant. These scale and solid deposits from tanks and scrubber equipment exposed to the limestone scrubbing liquor in the three systems were composed mainly of calcium, sulfite, sulfate, and carbonate in the ranges of percentages shown below.

Component	Percent by weight
CaO	26-41
SO_2	9-18
SO_3	24-47
CO_2	0.5-6

Soot that deposited in stacks above the gas reheater contained the following on a dry basis: 27 to 64% ash and 36 to 73% hydrocarbon. Moist soot contained 2 to 13% H_2O.

Exposed Specimens: Pictures were made of specimens when removed from the plant as shown in Figures 7-12. Then the specimens were cleaned and their corrosion rates and physical condition were determined as shown in Tables I through III along with properties of gas and liquor at various test points.

Inspections of Plant: Equipment in the plant systems was inspected for corrosion and erosion damage during the first week of February 1973.

Durometer "A" hardness values of rubber lining on equipment and on test specimens were measured with a Shore instrument--Type "A-2," ASTM 2240. Unfortunately, hardness of most lined plant equipment was not determined before plant operation; so data from the rubber vendors were ordinarily used as reference values. Temperature of the atmosphere varied from 35° to 60°F as did the temperature of equipment during the plant inspection. A decrease in temperature would be expected to increase rubber hardness. Values for neoprene linings are summarized in Table VI for the plant equipment and in Table VII for test specimens after exposure to plant operating conditions.

Results of Plant Inspections and Corrosion Tests

In this section, plant inspections are described first, and then the results of corrosion tests under different exposures in equipment are given. Some of the observations on plant equipment were made by or in collaboration with R. E. Wagner and R. C. Tulis, engineers with TVA at Shawnee Power Plant.

Carbon Steel Ducts for Inlet Stack Gas--Plant Equipment: A product of general corrosion thinly coated the inside walls of these ducts where they had been insulated. A thicker corrosion product covered inner walls of uninsulated duct sections (at flanges) because heat loss through bare metal to air cooled the stack gas and condensed corrosive liquid containing carbon dioxide, oxygen, and sulfur oxides. Such localized corrosion was pronounced in the Hydro-Filter duct; and subsequently in February 1973, the plant personnel fully insulated this duct as well as those to the other systems.

Small quantities of fly ash had deposited in ductwork areas where the gas flow changed directions, but this caused no apparent problem.

Stainless Steel Ducts for Inlet Stack Gas--Plant Equipment: In each duct between the carbon steel section and the scrubber unit there are: three nozzles of Type 316 stainless steel for spraying liquid to humidify gas, and one nozzle of Type 309 stainless steel for blowing air to dislodge soot. At the TCA and the Hydro-Filter (but not the venturi) scrubbers, there are four nozzles of Carpenter 20 alloy for spraying recycle slurry to cool the inlet gas.

The ducts, in general, were not appreciably corroded. Slight abrasion occurred in areas which were not coated by solids, but corrosion of the concentration cell type was present under the accumulations of solids.

Spray nozzles for gas humidification in these ducts were operated for the number of hours shown below.

Duct to	Spray hours	Percent of operating hours
Venturi	567	31
TCA	0	0
Hydro-Filter	2203	100

The conditions of the soot blower nozzles were as follows: at TCA--good, and at Hydro-Filter--severely corroded. (The nozzle in the venturi system was not inspected.) Nozzle corrosion at the Hydro-Filter was attributed to the use of the water sprays for gas humidification upstream which would yield hot corrosive mist containing carbon dioxide, oxygen, and sulfur oxides.

Two of the four nozzles of Carpenter 20 stainless steel used for cooling gas to the TCA scrubber were plugged and two were severely eroded internally. Erosion was caused by high-velocity flow of cooling slurry consisting of water, limestone, and fly ash.

Stainless Steel Ducts for Inlet Stack Gas--Corrosion of Test Specimens: Specimens located in ducts below gas humidifier sprays corroded as follows in mils per year: 1 to more than 330 in venturi system, 1 to 17 in TCA, and 1 to more than 300 in Hydro-Filter. (See points 1002, 2002, and 3002 on Figures 2-4.) The high rates in ducts to the venturi and Hydro-Filter systems are attributed to previously mentioned hot corrosive spray from humidifier spray operation. (Compare 1002, 2002, and 3002 on Figures 7, 9, and 11, respectively.) Type 316L showed good resistance in the venturi and TCA ducts but had localized attack (18-mil groove and minute pits) in the Hydro-Filter duct. Other, more expensive alloys, such as Hastelloy C-276 and Inconel 625, showed good resistance in the ducts to the three systems as well as in other parts of the systems as described later.

In the duct to the TCA system where no humidification was used, the temperature of the gas was 260° to 330°F, and the conditions of the nonmetal specimens were: Transite--good, Flakeline 200--fair, and Bonstrand--poor. All three of the materials were in poor condition in humidified gas to the venturi and Hydro-Filter units.

Venturi Scrubber--Plant Equipment: Bolts and nuts of Type 304 stainless steel used to assemble internal parts of the venturi scrubber had failed twice in plant operation before they were replaced with ones of fully annealed Type 316 stainless steel.

The neoprene-lined duct between the venturi unit and the after-scrubber tower was in good condition. Durometer A hardness of the lining was 67.

Venturi Scrubber--Corrosion of Test Specimens: The specimens were installed directly below the vertically mounted venturi as shown at point 1011 of Figure 2. Gas and slurry (laden with compounds of sulfur oxides) at a high velocity caused more severe corrosion and erosion damage to specimens in this location than in any other in the three systems. Specimens of nine alloys and three nonmetals failed. Figure 7 shows that spool 1011 was clean and only 8 of the 20 test specimens remained at the end of the 1840-hour test period. The five alloys that showed the lowest corrosion in mils per year were: Hastelloy C-276--5 mils, Inconel 625--5 mils, Incoloy 825--7 mils, Carpenter 20 Cb-3--14 mils, and Type 316L stainless steel--15 mils.

The other three remaining alloys and their corrosion rates were: Cupro-nickel 70-30--49 mils, Monel 400--57 mils, and Hastelloy B--100 mils.

The three rubbers (butyl, natural, and neoprene) were in good condition, but the plastic Qua-Corr failed as shown fourth from the left on 1011 in Figure 8. Both Figures 7 and 8 show severe erosion damage to the chemically resistant Teflon spacers on the spools at location 1011.

Towers in the Venturi, TCA, and Hydro-Filter Systems--Plant Equipment: In general, the neoprene lining on the wall of each tower was in good condition (Table VI). Hardness values and comments are listed below.

Tower	Durometer hardness		Comment
	Original[a]	Measured[b]	
Venturi (afterscrubber)	60-65	52-60	Wear was apparent in a small area near a nozzle. The highest hardness was near the top and the lowest was near bottom of the tower.
TCA	60-65	53-63	Highest hardness was in the midsection and the lowest was near bottom and top of the tower.
Hydro-Filter	60-65	65-72	Slight impact damage was probably caused by foreign sharp objects. Highest hardness was in the midsection and the lowest was near the top of the tower.

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[a] From vendor's data--hardness was not measured in the plant before tower operation.

[b] Measurements in plant were not made at same temperature because of weather changes.

Solids deposition in the towers varied as described below:

Venturi (afterscrubber)	A heavy deposit was present as follows: on the walls below trapout tray in bottom; on a 30-inch-wide band of the wall below the mist eliminator (chevron); and on bottom (1/2 the area) of the mist eliminator near top of tower.
TCA	Multilayered deposits of solids covered the walls of the tower. These decreased in thickness from 1 inch at bottom to 1/16 inch at top. The mist eliminator (chevron) was partly clogged. No loose solids were present because the unit was cleaned 2 weeks before the inspection.
Hydro-Filter	Scale, 1/16 inch thick, was on walls, piping, and spray nozzles. Slurry deposit was 1/4 to 1/2 inch thick on a narrow band of wall below and adjacent to the mist eliminator and on the bottom of the mist eliminator.

Corrosion of Type 316 stainless steel components of the towers ranged from mild to severe as described below.

Venturi (afterscrubber)	Surfaces under solid deposits had generally developed small pits. The wall of the outlet duct below the gas reheater, although clean, was pitted.
TCA	Grids that supported packing showed negligible corrosion, but their top surface showed some abrasion from the moving bed of wetted balls. The Koch FlexiTray was clean and showed no apparent corrosion after 985 hours' service. However, the top side of the mist eliminator (chevron) had undergone severe general corrosion and pitting after 1667 hours' service.
Hydro-Filter	Corrosion of the mist eliminator (chevron) and other components of Type 316L stainless steel in this tower was not detected.

Spray nozzles of Type 316 stainless steel were generally in good condition after handling slurry in the venturi afterscrubber and the TCA towers, but nonmetal nozzles in the Hydro-Filter tower were damaged. Four of 16 nozzle locations had been previously blanked when nozzles had failed and no spares were available. Some of the plastic nozzles beneath the glass sphere bed in the Hydro-Filter were damaged and had been replaced with nozzles of improved design. The remaining original nozzles were badly worn, and two of four improved design nozzles had failed. Of six soft rubber nozzles at a higher level in the Hydro-Filter, four were badly eroded; in one, the lining of the whirl chamber had torn so as to plug the outlet, and the casing was cracked.

Towers in the Venturi, TCA, and Hydro-Filter Systems--Corrosion of Test Specimens: In the afterscrubber of the venturi system, specimens were not installed because of plans to alter the arrangement of sprays.

In the TCA scrubber tower, test specimens were mounted at three elevations (see Figure 3 and Table II). Those above the third grid for holding mobile packing hollow plastic spheres at location 2006 were exposed to gas and liquor. Those below the FlexiTray at 2005 were exposed to gas and droplets, and those below the chevron mist eliminator at 2004 were exposed to gas and mist. Figure 9 shows that spools of specimens which had been exposed at 2006 and 2005 were partly covered by solids, but those at 2004 were clean. In the period August 12 through November 3, 1972, movement of the mobile bed had caused some erosion at 2006. The eroded specimens were replaced with new ones that were placed within a wire mesh container to protect them from erosion by the balls. At all three locations, the corrosion rates were 1 mil per year or less for Carpenter 20 Cb-3, Hastelloy C-276, Incoloy 825, Inconel 625, and

Type 316L stainless steel. Gas and mist at 2004 below the mist eliminator caused crevice corrosion on Incoloy 825 and minute pitting on Type 316L stainless steel. It also caused the greatest corrosion of mild steel (250 mils) and Cor-Ten B (268 mils per year). Pitting and/or crevice corrosion occurred on most of the other alloys exposed in this tower. The corrosion of stressed specimens 2004 shown in Figure 10 was about equal to that of the counterpart disk specimens in Figure 9.

The condition of the nonmetallic materials tested in the TCA tower ranged from poor to good. The three specimens of rubber and two of the three specimens of Bondstrand were in good condition.

In the tower of the Hydro-Filter system, tests of corrosion specimens were conducted at two locations (see Figure 4 and Table III). One was in the liquor and inlet gas at 3006 below the marble support grid, and the other was in the gas and liquor at 3005 above the marble bed (see Figures 11 and 12). All of the test specimens were coated with scale and deposit. The following alloys were corroded at rates of 1 mil per year or less: Carpenter 20 Cb-3, cupro-nickel 70-30, Hastelloy C-276, Incoloy 825, Inconel 625, and Type 316L stainless steel. Monel 400 and Hastelloy B had rates of less than 1 to 4 mils per year in the two locations. Mild steel and Cor-Ten B had the greatest rates--37 and 40 mils per year, respectively, above the marble bed; and 14 and 13, respectively, below the bed. Pitting and/or crevice corrosion occurred on the other alloys. In the liquor and inlet gas at 3006, Bondstrand was good, and the Flakeline and Transite were fair. In the gas and liquor at 3005, Bondstrand Qua-Corr, and the three rubbers were good, and the Flakeline was fair.

Exhaust Gas Systems--Plant Equipment: Each exhaust gas reheater for heating the scrubbed gas to between 235° and 265°F is identical in the three systems (Figures 2, 3, and 4). The refractory lining, 3 inches thick, in all the reheaters had cracked, mainly near the burner ports. The lining of the venturi reheater had the largest cracks and was coated with fuel oil.

In the venturi stack, soot saturated with oil had deposited, and on two occasions such a deposit had ignited and burned. In the TCA exhaust stack, soot saturated with oil was also found, but no fires had occurred. In the Hydro-Filter system, the soot deposit in the exhaust duct was thinner, indicating that combustion of fuel oil in the heater had been more efficient than in the other two systems.

Downstream from the reheater in each system, there was no apparent corrosion of the stack made of Type 316 stainless steel.

At the induced-draft (I. D.) fan of each system, soot and fly ash accumulated on the fan blades and housing to depths of 1/16 to 1/4 inch. In general, the thickest deposits were on stationary parts, and the trailing faces of the blades accumulated a thicker deposit than other areas of moving parts. Deposits were smallest in the fan for the Hydro-Filter where no oil was detected. Measurements of the blades and shrouds of Type 316 stainless steel showed only slight variation in thickness from the original values determined before the plants were operated. Slight bends on the periphery of two blades on the fan for the Hydro-Filter and one blade on the fan for the TCA system probably occurred because of stress relieving, but these bends caused no apparent problems.

A stainless steel sleeve (40-inch diameter by 4 feet high) has subsequently been installed in each reheater. Also, burner nozzles of different design and having much better atomizing characteristics were installed. The sleeve and nozzles should promote essentially complete combustion of oil before hot combustion gases combine with the scrubber exhaust gas and thus should minimize problems with oil and soot deposits in the stack and fan.

Exhaust Gas Systems--Corrosion of Test Specimens: Corrosion test specimens were mounted in the exhaust stacks in each system 8 to 10 feet downstream from the reheater as shown at points 1007, 2007, and 3007 (Figures 2, 3, and 4). Temperature of heated exhaust gas in contact with the specimens was usually between 235° to 265°F. Tables I, II, and III give corrosion data. Figures 7 through 12 show the soot- and ash-covered specimens after exposure.

In the stack of the venturi system, the corrosion of the test specimens was slightly more severe than in other systems. Oil-saturated soot had caught fire and destroyed the Teflon insulators and spacers. (See item 1007 on Figures 7 and 8.) Five of the highly alloyed materials and Type 316L stainless steel were durable, however, corroding at rates of less than 1 mil per year. Five other alloys had corrosion rates of 1 to 5 mils per year, and the rates for mild steel and Cor-Ten B were 16 and 18 mils. Aluminum 3003 was pitted to a depth of 70 mils during the exposure period. Transite was in good condition after the test, but Bondstrand and Flakeline failed apparently because of overheating.

In the TCA exhaust stack, the corrosion rate was either negligible or less than 1 mil per year for eight alloys including Type 316L. (See item 2007 on Figures 9 and 10.) Cor-Ten B and mild steel had rates of 2 and 3 mils per year with minute pits. Pitting of other alloys ranged from minute to depths of 12 mils. Flakeline 200 and Transite were in good condition but Bondstrand failed.

In the stack of the Hydro-Filter system, corrosion of specimens was slightly greater than in the TCA system but less than in the venturi system. (See item 3007 on Figures 11 and 12.) Five alloys, including Type 316L stainless steel which had minute pits, were corroded at rates less than 1 mil per year. Several alloys were pitted, and the deepest pit was 18 mils in E-Brite 26-1. Attack of mild steel, Cor-Ten B, and aluminum 3003 was 4 to 5 mils per year with crevice corrosion under the Teflon insulator. Flakeline and Transite were in good condition, but Bondstrand failed.

Corrosive attack of the stressed specimens by reheated stack gas was about equal to that of the counterpart disks in each test.

Effluent Hold Tanks--Plant Equipment: An effluent hold tank 20 feet in diameter and 21 feet tall is located directly under each scrubbing tower: D-101 for the venturi, D-201 for the TCA, and D-301 for the Hydro-Filter systems. The shells are made of A-283 carbon steel coated inside (80 mils minimum thickness) with Flakeline 103 manufactured by the Ceilcote Company. This coating is a Bisphenol-A type of polyester resin filled with flake glass (25-35%).

Each tank was in good condition except for minute cracks at the junction of some baffles with the tank walls. Stains of iron rust indicated that the cracks penetrated the Flakeline coating. All cracks were within 8 feet of the bottom of a tank. The neoprene-lined agitators were in good condition, and only slight wear was noted on the leading edge of the blades. The hardness of the neoprene had changed little if any (see Table VI). The Bondstrand 5000 and the Type 316L stainless steel downcomers showed no evidence of attack in either tank. In tanks D-101 and D-301 there were slightly worn areas where the butyl rubber insulator on the specimen suspension pipe (15 feet long) had rubbed the wall.

Effluent Hold Tanks--Corrosion of Test Specimens: Corrosion test specimens were mounted in the effluent hold tanks 15 feet below the top. Figures 2 through 4 identify the locations and Figures 7 through 12 show pictures of test specimens by numbers--1008 for the venturi, 2008 for the TCA, and 3008 for the Hydro-Filter systems. Tables I through III show that corrosion was less than 1 mil per year for several alloys in the three tanks.

In the venturi system tank, nine alloys, including Type 316L stainless steel, had corrosion rates of 1 mil per year or less without localized attack. The eight other alloys were attacked locally and had corrosion rates of 1 to 18 mils per year. Four specimens were pitted up to 24 mils deep. Crevice corrosion occurred on eight specimens. The rate for mild steel was 18 mils and that for Cor-Ten B was 14 mils per year, both with crevice corrosion.

The TCA effluent hold tank was in use only during the last 45 hours of the 1667-hour operating period, so corrosion rates are less representative than those at the two other tanks which were used continually during operating periods. Corrosion was less than 1 mil per year for nine alloys. Appreciable corrosion in mils per year occurred to several metals as follows: aluminum 3003, 20; Cor-Ten B, 170; and mild steel, 210. Apparently significant general corrosion of these alloys occurred during the extended period that the tank was idle, but there was only minute pitting and no crevice corrosion.

In the Hydro-Filter tank, corrosion was less than 1 mil per year for 10 alloys, including Type 316L stainless steel, without localized corrosion. Aluminum 3003, mild steel, and Cor-Ten B were corroded at the greatest rates--2 to 5 mils per year. Pitting occurred on three alloys, and the deepest pit was 5 mils on Type 304L stainless steel. Crevice corrosion occurred on 7 alloys.

In all three of the effluent hold tanks, the following showed good resistance: the butyl, neoprene, and natural rubbers; the Bondstrand and Qua-Corr plastics; and the Transite. Because of abrasion on one face, the specimens of Flakeline 200 were in only fair condition. Flakeline 200 is similar to Flakeline 103 except that it is formulated for application by "brush or spray" instead of by "trowel or spray." Apparently, the application of Flakeline 103 coating inside the effluent tanks was superior to that of Flakeline 200 on the test specimens.

Recirculation Tanks--Plant Equipment: Each of the scrubbing systems has a recirculation tank 5 feet in diameter by 21 feet tall as follows: D-104 for the venturi, D-204 for the TCA, and D-304 for the Hydro-Filter. These tanks were lined with neoprene sheet 1/4 inch thick, and the blades and shaft of their agitators were also lined with neoprene.

The linings on all of the tank walls and the agitators were in good condition. A thin scale had deposited that would protect the surface. Durometer A hardness values for the neoprene linings, however, were not consistent (see Table VI). The hardness values were higher than the original for the lining in Hydro-Filter tank D-304, and they were lower for the agitator blades in TCA tank D-204.

Recirculation Tanks--Corrosion of Test Specimens: Corrosion test specimens were suspended 8 feet below the top in recirculation tanks D-104 (venturi) and D-304 (Hydro-Filter); they were 15 feet below the top in D-204 (TCA). See Figures 2, 3, and 4. Corrosion was negligible or less than 1 mil per year for several alloys in the three tanks (Tables I through III). The greatest attack occurred on Cor-Ten B and mild steel. Items 1012, 2012, and 3012 on Figures 7, 9, and 11, respectively, show the spools of specimens after exposure.

In venturi tank D-104, the rate for Cor-Ten B was 12 and that for mild steel was 19 mils per year. The rate of attack on the other alloys was less than 1 mil per year. Pitting and crevice corrosion occurred only on Type 410 stainless steel.

In TCA tank 204, the corrosion rate was 5 mils per year for Cor-Ten B, 5 mils for mild steel, and 2 mils for aluminum. Pitting occurred on seven alloys with the maximum depth of 10 mils on Type 304L stainless steel. Crevice corrosion occurred on four alloys.

In Hydro-Filter tank D-304, the corrosion rate was 10 mils for Cor-Ten B and 11 mils per year for mild steel. Type 410 had pits 7 mils deep and three alloys underwent crevice corrosion. The other alloys were attacked less than 1 mil per year.

In general, localized attack was less prevalent in the recirculation tanks where agitation was more vigorous than in the effluent hold tanks (except in D-201 that was used only 45 hours).

Bondstrand and Transite were in good condition after the test in each tank, but Flakeline 200 was only fair because of abrasion on one face of each specimen.

Clarifier Tanks--Plant Equipment: Clarifier tanks D-102 for the venturi and D-302 for the Hydro-Filter are 20 feet in diameter and 15 feet tall; and tank D-202 for the TCA is 30 feet in diameter by 15 feet tall. Each tank has a coned bottom that is positioned 3 to 5 feet above the foundation elevation (Bechtel drawings M-8 and M-9). The tanks are of A-283 carbon steel coated inside with Flakeline 103. Mechanical equipment inside the clarifiers is made of Type 316L stainless steel. Tank D-302 was not inspected because it was in use for testing filter equipment.

The Flakeline 103 coating in tanks D-102 and D-202 was in good condition except for cracks at the junction of the overflow weir and the wall. Iron rust had bled through the cracks. The stainless steel equipment had not been attacked. However, four carbon steel bolts used to anchor the underflow cone at the bottom of the two tanks had rusted.

Clarifier Tank--Corrosion of Test Specimens: A spool of corrosion test specimens was suspended in the fluid 5 feet below the weir in clarifier tanks D-102, D-202, and D-302. These tanks are not shown in Figures 2 through 4 (see Bechtel drawings M-8 and M-9). Items 1013, 2013, and 3013 in Figures 7, 9, and 11 are pictures of specimens after exposure. Tables I through III show corrosion data.

In the venturi tank D-102, seven alloys including Types 304L and 316L stainless steel showed negligible corrosion, and two other alloys had rates of 1 mil per year or less without localized attack. Cor-Ten B and mild steel had rates of 5 mils per year. Pitting occurred on four alloys, and the greatest depth was 12 mils on aluminum 3003. Five alloys had undergone crevice corrosion.

In the TCA tank D-202, six alloys including Type 304L and Type 316L stainless steel showed negligible attack and seven other alloys had rates of 1 mil per year or less without localized attack. Cor-Ten B and mild steel were corroded at rates of 6 and 8 mils per year. Two alloys were pitted; the deepest pit was 4 mils on Type 410 stainless steel. Localized corrosion occurred on Cor-Ten B and Type 410 stainless steel.

In the Hydro-Filter tank D-302, a total of nine alloys including Type 304L and Type 316L stainless steel corroded at less than 1 mil per year without localized attack. The rates were 7 and 9 mils for Cor-Ten B and mild steel. Four alloys were pitted; Type 410 stainless steel had the deepest pit, 16 mils, and four alloys had undergone crevice corrosion.

Transite was in good condition in the three clarifier tanks; Bondstrand was good in the venturi and the TCA tanks but poor in the Hydro-Filter tank because of spalling; Flakeline 200 was fair in the three tanks.

Clarified Process Water Storage Tanks--Plant Equipment: Clarified water storage tank D-103 for the venturi and D-303 for the Hydro-Filter systems are 10 feet in diameter and 9 feet tall. Tank D-203 for the TCA system is 13 feet in diameter and 9 feet tall. Each tank has four baffles and a shell of carbon steel lined with 1/4 inch of neoprene of durometer A hardness of 55-60. Each tank has a three-blade agitator with diameter as follows: 14 inches in D-103 and D-303 and about 42 inches in D-203. The agitators and shafts are lined with neoprene.

Conditions of linings in the clarified water tanks are described below.

Tank	Tank No.	Condition of lining on
Venturi	D-103	Tank: Excellent Agitator: Noticeable wear
TCA	D-203	Tank: A lap joint, 8 inches long, was loose where bottom liner extends upward 1-1/2 inches to make overlap on wall liner near a baffle on west side. Agitator: Slight wear
Hydro-Filter	D-303	Tank: Good Agitator: Noticeable wear. Cuts at several places were possibly made by sharp foreign objects.[a]

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[a] Two pieces of thin gage metal were on floor of tank.

It appears that the durometer A hardness of the neoprene might have increased slightly up to 11 units above 60 as shown in Table VI. However, the temperature (60°F) of the linings during the inspection was lower than the standard (73°F) specified in the ASTM designation, D2240-68.

Reslurry Tank--Plant Equipment: Tank D-401 is used for reslurrying waste solids removed in the clarifier. It is identical in size and in construction to storage tank D-103 already described. All the neoprene linings were in good condition and hardness tests were not made.

Neoprene-Lined Centrifugal Pumps--Plant Equipment: During the corrosion tests in the scrubbing systems, Hydroseal pumps were in service; impeller diameters were 12, 17, or 20 inches. These centrifugal pumps were manufactured by the Allen-Sherman-Hoff Company. All wetted parts were lined with neoprene of a durometer A hardness specified to be 54 to 56.

When the pumps were dismantled, inspection showed that the linings were not damaged severely in any except pumps discussed later. However, wear of varying degrees was found. The grooving of neoprene linings on impellers and casings was least in the TCA system and greatest in the Hydro-Filter system. General wear of the linings was slight, but a little more noticeable in the Hydro-Filter system. A durometer A hardness of the liners ranged up to 16 above the specified maximum; this was fairly general for the three systems. (The temperature of the linings when tested was below the standard of 73°F; this would cause higher values.)

Packing glands caused severe wear on the stainless steel components of pumps G-102 and G-202; these are the thickener underflow pumps for slurry containing about 30% solids.

The output of slurry feed pumps, G-108 and G-208, had decreased over a period of weeks. These are rotary screw-type pumps (Moyno) used for pumping limestone slurry containing about 60% solids. Inspection revealed that increased clearance between the stator and the rotor, because of wear of the rubber lining of the stator, allowed excess leakage. This was corrected by replacement of worn parts.

Pump G-401, reslurry tank pump, was dismantled for modification. The rubber-lined impeller and casing were neither grooved nor worn appreciably. Hardness values of the linings were not determined.

Some of the Hydroseal pumps have been replaced since February with Centriseal pumps produced by the same manufacturer. Sealwater required at the Hydroseal pumps had added more water to the system than could be tolerated for closed-loop operation.

Valves--Plant Equipment: The stainless steel check valves at the discharge of several pumps for each scrubber system were inspected. These valves are ASTM A-351, Grade CF-8M body, Type 316 plate, and neoprene seal. Generally, these valves had worn slightly and their surfaces were smooth and polished.

The 4-inch neoprene pinch valve upstream (of FE 1061) from the bottom slurry header in the afterscrubber tower of the venturi system showed no signs of chemical attack and only slight evidence of wear.

Piping--Plant Equipment: Neoprene-lined piping was inspected at the inlet to all pumps that were dismantled for inspection or seal modification in the three scrubber systems. Elbows, tees, and open ends of the piping showed no evidence of wear or deterioration. The neoprene lining 3/16 inch thick with a specified durometer A hardness of 50 plus or minus 5 was applied by the Rubber Applicators, Houston, Texas. Hardness values were not determined during the inspection.

Discussion

Process Materials: In the SO_2 removal plant, the inlet stack gas, the limestone absorbent, and their reaction products are corrosive or abrasive. Components of stack gas, such as CO_2, O_2, and SO_2, dissolve sparingly to make condensate or water corrosive. Fly ash in stack gas and the limestone in absorbent slurry are abrasive, especially in high-velocity streams. Slurry containing limestone, sulfite, sulfate, and fly ash forms deposits on metal to cause localized corrosion. (In future tests, chloride in gas or in makeup water should be considered along with compounds of sulfur as a likely corrosive in areas where it might be concentrated in a residue.)

Materials of Construction: Materials in the plant consist mainly of: carbon steel in the inlet duct for stack gas from the power plant; stainless steel, Type 316L in the scrubbing system ducts, the venturi scrubber, removable internal parts of scrubber towers, the outlet gas duct, the fans, and stack; neoprene-lined carbon steel in the venturi afterspray, TCA, and Hydro-Filter towers; neoprene-lined carbon steel in the recirculation, clarified process water, and reslurry tanks; Bondstrand and Type 316L stainless steel downcomers to the effluent hold tank; Flakeline 103-lined carbon steel in the effluent hold and clarifier tanks; refractory-lined gas reheater; and neoprene-lined pumps and piping.

Corrosion--Plant Equipment: In general, materials used in construction of the three scrubbing systems showed good resistance to attack. Carbon steel ducts were slightly attacked by inlet stack gas when at temperature below the dew point.

Inlet stack gas, after being humidified by spray water, attacked stainless steel ducts and nozzles as follows: slight erosion of bare duct surfaces; concentration cell-type corrosion (pitting and crevice) of surfaces underlying deposits; and severe corrosion and erosion of surfaces (nozzles or projections) subjected to impingement.

In the venturi scrubber, the limestone slurry and gas discharging at high velocity corroded and eroded stainless steel parts, but apparently did not damage neoprene lining in the duct.

In the towers of the three systems, slurry and gas flowing at low velocity caused only slight corrosion and erosion of bare removable parts of stainless steel, such as packing supports and FlexiTrays. Movement of the mobile packing (hollow plastic spheres similar to Ping-Pong balls) caused some erosion of grid wire in the TCA absorber.

Cause for severe corrosion on the top surface of a chevron-type mist eliminator in the TCA tower is not known. However, it is likely that some mist passing through a Koch FlexiTray located below would collect on the chevron mist eliminator and evaporate to form a residue high in compounds of chlorine and sulfur which would be corrosive. Pits observed in the outlet duct from the venturi afterscrubber might also have been caused by such a residue of chlorine and sulfur compounds. Periodic washing to remove residue might decrease the corrosion.

Nozzles of stainless steel were more durable than those of rubber or plastic for spraying limestone slurry in the towers.

Rubber lining on the tower shells, though coated usually with slurry solids, was generally in good condition.

Exhaust gas stacks of Type 316L stainless steel were apparently in good condition after exposure to gas reheated to between 235° and 265°F. Sleeves and improved burner nozzles installed at the gas reheaters should improve fuel oil combustion and thereby minimize troublesome soot deposition and a potential fire hazard in exhaust gas stacks.

Flakeline 103 linings in the effluent hold tanks and clarifier tanks were generally in good condition except for cracks near attachments, such as baffles and weirs, to the walls. Bondstrand downcomers were in good condition to effluent hold tanks.

Neoprene linings were in good condition in the recirculation, clarified water, and reslurry tanks. Slight to noticeable wear was apparent on neoprene-lined agitators in these tanks. Neoprene-lined piping was inspected near pumps and it appeared to be in good condition. The neoprene linings of casings and impellers in centrifugal pumps were not severely damaged, and the least wear was on those in the TCA system and the greatest on those in the Hydro-Filter system. Decreased output of limestone slurry (60% solids) by two rotary screw-type pumps (Moyno) required that neoprene-lined stators be replaced. The rotors are of stainless steel.

Corrosion--Test Specimens: In general, the least attack occurred to test specimens in the TCA system and the greatest to those in the venturi system. With few exceptions, the greatest loss of weight from metal specimens occurred in inlet duct areas exposed to wetted flue gas and in venturi outlet area exposed to slurry and gas at comparatively high velocities. Damage to some nonmetallic materials occurred in these areas also. Slurry impingement on the specimens caused erosion and corrosion. Pitting and crevice-type corrosion were minor where erosion and general corrosion kept the specimens clean. Generally, in most areas where solids accumulated in the three scrubber systems, the surface of the underlying specimens showed localized corrosion. However, each of the 17 alloys tested showed good resistance at one or more test locations in each scrubber system. The three rubbers were tested at only six locations; they showed good resistance in all tests. The maximum service temperature was exceeded for some nonmetallic materials in the inlet gas duct and exhaust gas duct.

Table VIII is a summary of data from all the corrosion tests conducted in the three different scrubber systems. It shows the comparative resistance of the materials tested without identifying the test conditions. The metals are grouped into four categories with respect to decreasing corrosion resistance. The evaluation is based on corrosion rates determined by weight loss and/or resistance to pitting, crevice corrosion, and other types of localized attack.

Corrosion of Hastelloy C-276 was negligible to 5 mils per year; this alloy showed no evidence of localized attack in any test location. Next in resistance were the alloys Inconel 625, Incoloy 825, Carpenter 20 Cb-3 and Type 316L stainless steel with corrosion rates ranging from negligible to 5, 7, 14, and 15 mils per year, respectively. These alloys had very few pits and/or corrosion crevices. One specimen of Type 316 stainless steel was grooved and the weld of another was attacked.

Three nonferrous alloys, cupro-nickel 70-30, Monel 400, and Hastelloy B, had minimum rates of less than 1 mil and maximum rates of 49, 57, and 100 mils per year, respectively, with one or two specimens pitted. In three tests of Monel and in one test of cupro-nickel 70-30, the welds were inferior to the parent metal.

A group of five alloys that included Type 446 stainless steel, E-Brite 26-1, Incoloy 800, USS 18-18-2, and Type 304 stainless steel, had rates that ranged from negligible to a "greater than" value which indicates that the specimen was completely destroyed at one or more test locations. The values for failures ranged from greater than 140 mils per year for Type 446 to greater than 200 for both USS 18-18-2 and Type 304L stainless steels. These five alloys were highly susceptible to localized corrosion.

Another group of alloys which consisted of Type 410 stainless steel, aluminum 3003, mild steel A-283, and Cor-Ten B had minimum rates of less than 1 mil per year and maximum rates of greater than 250 for Type 410 to greater than 1400 for mild steel and Cor-Ten B. Pitting and crevice corrosion occurred on these four alloys.

In general, the stressed specimens (5 alloys only) were not corroded at rates higher than their counterpart disk-type specimens, and no cracks were observed.

Of all the alloys tested, Hastelloy C-276 was the most durable and also the most expensive. Type 316L ranked fifth in durability and about eleventh in cost. The values for cost comparison are based on costs of tubing and sheet with Type 304 stainless steel as unity (1.00). (See Table VIII.)

Specimens of Bondstrand 4000, Flakeline 200, and Transite were tested at 21 locations. Bondstrand showed good resistance in 12 tests and poor in 9 tests. The evaluations for Flakeline were: 2 good, 14 fair, and 5 poor; and those for Transite were: 14 good, 2 fair, and 5 poor. Only six specimens of each of the plastic Qua-Corr and of the rubbers, butyl, natural, and neoprene, were tested. The results were five good and one poor for Qua-Corr and six good for each of the rubbers.

Summary

Test specimens and equipment exposed for about 6 months in three test SO_2 removal systems at Shawnee Power Plant were evaluated for corrosion and wear.

The most severe damage occurred in plant areas exposed to humidified stack gas containing fly ash, CO_2, O_2, and SO_2 at elevated temperature and high velocity; to gas and slurry discharging at high velocity from the venturi; and to gas and mist leaving an absorber.

Metals covered by limestone-fly ash deposits were not eroded but were subject to corrosion of the concentration cell type.

Neoprene-lined towers, ducts, and tanks, as well as rubber-lined test specimens, were durable. Some wear was apparent on neoprene linings of pumps and agitators.

In limited tests, reinforced plastics, such as polyester, epoxy, and furan, were less durable than rubber as lining materials.

Seventeen alloys were tested in twenty-one exposure areas in three systems of the plant. The maximum corrosion rates in mils per year for the five most durable specimens were as follows: Hastelloy C-276, 5 mils; Inconel 625, 5 mils; Incoloy 825, 7 mils; Carpenter 20 Cb-3, 14 mils; and Type 316L stainless steel, 15 mils. Hastelloy C-276 is the most durable and expensive of all the alloys tested; Type 316L stainless steel ranks fifth in durability and about eleventh in cost.

This corrosion study is being continued on materials of construction for the SO_2 removal test facility at Shawnee Power Plant.

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TABLE I

Corrosion Tests Conducted in the Venturi System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--Aug. 12, 1972, to Feb. 2, 1973, operating time--1840 hours or 76.7 days; and idle time--2340 hours or 97.5 days)

Corrosion specimens						
Exposed in	Inlet gas	Gas and spray	Exhaust gas (heated)	Effluent liquor	Recycle liquor	Liquor in clarifier
Locations (See Fig. 2), Reference No.	1002	1011	1007	1008	1012	1013
Gas						
Temperature, °F	275-330^{a}	80-170	235-265	-	-	-
Velocity, ft/sec	20-60	15-45	20-60	-	-	-
Flow rate, 1000's of actual ft^3/min	10-30	8-23	10-30	-	-	-
Composition, % by volume						
SO_2	0.3	0.2	0.2	-	-	-
CO_2	13	12	12	-	-	-
N_2	74	69	69	-	-	-
O_2	4.5	4	4	-	-	-
H_2O	8	15	15	-	-	-
Fly ash, gr/standard ft^3	3-5	0.02	0.02	-	-	-
Liquor						
Temperature, °F	-	-	-	90-130	70-125	70-100
Solids, % by weight	-	-	-	4-10	4-10	0-20
pH	-	-	-	5.8-6.8	5.6-6.3	6.0-7.0
Composition, % by weight						
$CaSO_4 \cdot 2H_2O$	-	-	-	1.0-2.0	1.0-2.0	0-4
$CaSO_3 \cdot 1/2H_2O$	-	-	-	1.5-3.5	1.5-3.5	0-7
Unreacted limestone plus fly ash	-	-	-	1.5-4.5	1.5-4.5	0-10
Water	-	-	-	90-96	90-96	80-100
Corrosion rate of metals^{b}, mils/yr						
Aluminum 5005, weld ER1100	> 160	> 550	P70	P24, -^{c}	< 1	P12, -^{c}
Carpenter 20Cb-3, weld Carpenter 20Cb-3	< 1	14	< 1	Neg.	Neg.	Neg.
Carpenter 20Cb-3, weld Carpenter 20Cb-3, stressed	-	-	< 1	Neg.	-	-
Cor-Ten B, weld E8018-C3	> 290	> 1400	18, -^{d}	14, -^{c}	12	5, -^{c}
Cupro-nickel 70-30, weld B259 RCuNi	13	49	P18, -^{d}	1	< 1	1
E-Brite 26-1, weld E-Brite 26-1	> 140	> 190	Pm, -^{d}	< 1	Neg.	Neg.
E-Brite, 26-1, weld E-Brite 26-1, stressed	-	-	< 1	Neg.	-	-
Hastelloy B, weld Hastelloy B	28	100	-^{d}	2, Pm	< 1	< 1, Pm
Hastelloy C-276, weld Hastelloy C-276	< 1	5	-^{d}	Neg.	< 1	Neg.
Incoloy 800, weld Inconel 82	48, -^{e}	> 190	< 1	< 1	< 1	Neg.
Incoloy 825, weld Incoloy 65	< 1	7	< 1	< 1	< 1	< 1
Incoloy 825, weld Incoloy 65, stressed	-	-	1	Neg.	-	-
Inconel 625, weld Inconel 625	< 1	5	< 1	< 1	Neg.	Neg.
Mild steel A-285, weld E6012	> 330	> 1400	16, -^{c}	18, -^{c}	19	5
Monel 400, weld Monel 60	10	57^{f}	4	1	< 1	1, P2
Type 304L, weld Type 308L	65, -^{e}	> 200	1	< 1, -^{c}	Neg.	Neg.
Type 304L, weld Type 308L, stressed	-	-	2	< 1, -^{c}	-	-
Type 316L, weld Type 316L	1	15, -^{f}	< 1	Neg.	< 1	Neg.
Type 316L, weld Type 316L, stressed	-	-	< 1	Neg.	-	-
Type 410, weld Type 309	> 130	> 250	5, -^{d}	P12, -^{c}	P3, -^{c}	< 1, -^{c}
Type 446, weld Type 309	> 103	> 140	1	< 1, -^{c}	Neg.	< 1, -^{c}
USS 18-18-2, weld Inconel 82	> 140	> 200	2	P5, -^{c}	Neg.	P10, -^{c}
Evaluation of nonmetallic materials^{g}						
Plastics						
Bondstrand 4000 (Fiber glass-reinforced epoxy)	Poor	Poor	Poor	Good	Good	Good
Flakeline 200 (Inert flakes and polyester resin)	Poor	Poor	Poor	Fair^{h}	Fair^{h}	Fair^{h}
Quo-Cor (Fiber glass-reinforced furan resin)	-	Poor	-	Good	-	-
Rubbers						
Butyl 19,844 (Copolymer of isobutylene-isoprene)	-	Good	-	Good	-	-
Natural 1575 (Polyisoprene)	-	Good	-	Good	-	-
Neoprene 3150 (Chloroprene polymer)	-	Good	-	Good	-	-
Ceramic						
Transite (Portland cement and asbestos)	Poor	Poor	Good	Good	Good	Good

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[a] No spray water was used to humidify the gas when the temperature was 275°-330°F; temperature was 125°F for 967 hours when spray water was used.

[b] The "greater than" (>) sign is used when a specimen was completely destroyed. "P" preceding a number indicates pitting during the exposure period to the depth in mils shown by the number, and "Pm" indicates minute pits. "Neg.," negligible, no weight loss or localized attack.

[c] Crevice corrosion at Teflon insulator.

[d] There was some weight loss of specimen due to wear at center hole after Teflon insulators failed when overheated.

[e] Severe localized attack of parent metal.

[f] Attack of weld.

[g] Evaluation: Good, little or no change in condition of specimen; fair, definite change, probably could be used; poor, failed or severely damaged.

[h] Evidence of abrasion on edge of specimen.

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TABLE II

Corrosion Tests Conducted in the TCA System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--Aug. 12, 1972, to Feb. 3, 1973; operating time--1667 hours or 69.5 days; and idle time--2535 hourr or 105.6 days)

Corrosion specimens								
Exposed in	Inlet gas	Gas and liquor	Gas and droplets	Gas and mist	Exhaust gas (heated)	Effluent liquor	Recycle liquor	Liquor in clarifier
Locations (See Fig. 3), Reference No.	2002^a	2006^b	2005	2004	2007	2008^c	2012	2013
Gas								
Temperature, °F	260-310	70-125	70-120	70-120	235-265	-	-	-
Velocity, ft/sec	25-60	6-12	5-10	4-8	25-60	-	-	-
Flow rate, 1000's of actual ft^3/min	15-30	11-22	11-22	11-22	15-30	-	-	-
Composition, % by volume								
SO_2	0.3	0.05	0.05	0.05	0.05	-	-	-
CO_2	13	12	12	12	12	-	-	-
N_2	74	69	69	69	69	-	-	-
O_2	4.5	4	4	4	4	-	-	-
H_2O	8	15	15	15	15	-	-	-
Fly ash, gr/standard ft^3	3-5	0.02	0.02	0.02	0.02	-	-	-
Liquor								
Temperature, °F	-	-	-	-	-	110-125	85-125	85-100
Solids, % by weight	-	-	-	-	-	6-10	7-15	0-30
pH	-	-	-	-	-	5.9-6.3	5.6-6.4	6.3-7.6
Composition, % by weight								
$CaSO_4 \cdot 2H_2O$	-	-	-	-	-	1.0-2.0	1.5-3.0	0-6
$CaSO_3 \cdot 1/2H_2O$	-	-	-	-	-	2.0-3.5	2.5-5.0	0-10
Unreacted limestone plus fly ash	-	-	-	-	-	3.0-4.5	3.0-7.0	0-15
Water	-	-	-	-	-	90-94	85-93	70-100
Corrosion rate of metals^d, mils/yr								
Aluminum 3003, weld ER1100	2	4, >^{e}	4	26, P20	1, P2	20	2, P2	1
Carpenter 20Cb-3, weld Carpenter 20Cb-3	< 1	Neg.	< 1	< 1	< 1	Neg.	< 1	Neg.
Carpenter 20Cb-3, weld Carpenter 20Cb-3, stressed	-	-	-	1	< 1	2	-	-
Cor-Ten B, weld E8018-C3	15, Pm	13	21, P5	268	2, Pm	170, Pm	5, Pm	6, >^{f}
Cupro-nickel 70-30, weld E259 RCuNi	2	< 1, >^{g}	2, >^{h}	17	< 1	3	< 1	< 1
E-Brite 26-1, weld E-Brite 26-1	< 1	P2, >^{e}	P6	1, Pm	P2	Neg.	Neg.	Neg.
E-Brite 26-1, weld E-Brite 26-1, stressed	-	-	-	Pm	Pm	< 1	-	-
Hastelloy B, weld Hastelloy B	< 1	6	6	13	< 1	2	< 1	< 1
Hastelloy C-276, weld Hastelloy C-276	< 1	Neg.	< 1	Neg.	Neg.	Neg.	< 1	Neg.
Incoloy 800, weld Inconel 82	< 1	>^{e}, >^{g}	P8, >^{e}	P19, >^{e}	Pm	Neg.	P2	Pm
Incoloy 825, weld Incoloy 65	< 1	< 1, >^{g}	Neg.	>^{e}	Neg.	Neg.	Neg.	Neg.
Incoloy 825, weld Incoloy 65, stressed	-	-	-	1, >^{e}	< 1	< 1	-	-
Inconel 625, weld Inconel 625	< 1	Neg.	Neg.	Neg.	< 1	Neg.	Neg.	< 1
Mild steel A-283, weld E6012	17	26	23	P50	3, Pm	210, Pm	3	8
Monel 400, weld Monel 400	1	1	1	15, >^{i}	< 1	2	< 1	< 1
Type 304L, weld Type 308L	< 1, Pm	P6, >^{e}	P13, >^{e}	P23, >^{e}	P16	Pm	P10, >^{e}	Neg.
Type 304L, weld Type 308L, stressed	-	-	-	4, >^{e}	< 1	Neg.	-	-
Type 316L, weld Type 316L	< 1	Neg.	< 1	Pm	< 1	< 1	< 1	Neg.
Type 316L, weld Type 316L, stressed	-	-	-	< 1, >^{e}	< 1	< 1	-	-
Type 410, weld Type 309	1, Pm	Pm, >^{e}	P6, >^{e}	P12, >^{e}	P12, >^{e}	Pm	Pm, >^{e}	P4, >^{e}
Type 446, weld Type 309	< 1	P5, >^{e}	P19, >^{e}	P18, >^{e}	P6	< 1	P7, >^{e}	< 1
USS 18-18-2, weld Inconel 82	< 1	P4, >^{e}	P8, >^{e}	P16, >^{e}	P5	< 1	Pm, >^{e}	< 1
Condition of nonmetallic materials^j								
Plastics								
Bondstrand 4000 (Fiber glass-reinforced epoxy)	Poor	Poor	Good	Good	Poor	Good	Good	Good
Flakeline 200 (Inert flakes and polyester resin)	Fair	Poor	Fair	Fair	Good	Fair	Fair	Fair
Qua-Corr (Fiber glass-reinforced furan resin)	-	-	-	Good	-	Good	-	-
Rubbers								
Butyl 26,666 (Copolymer of isobutylene-isoprene)	-	-	-	Good	-	Good	-	-
Natural 1375 (Polyisoprene)	-	-	-	Good	-	Good	-	-
Neoprene 9150 (Chloroprene polymer)	-	-	-	Good	-	Good	-	-
Ceramic								
Transite (Portland cement and asbestos)	Good	Poor	Fair	Poor	Good	Good	Good	Good

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[a] No spray water was used at test location 2002 during the corrosion test period to humidify the gas.

[b] Because test specimens were worn by movement of plastic balls during the period 8/12 to 11/3/72, new specimens were installed 11/17/72. The data given were determined from the last 995 hours of operation.

[c] The specimens were immersed in the slurry only during the last 44.5 hours of operating time, and the corrosion rate was determined on this basis. However, the high rates for aluminum, Cor-Ten B, and mild steel indicate that these alloys were corroded during idle time also.

[d] The "greater than" (>) sign is used when a specimen was completely destroyed. "P" preceding a number indicates pitting during exposure period to depth in mils shown by number, and "Pm," minute pits. "Neg.," negligible, no weight loss or localized attack.

[e] Crevice corrosion at contact with Teflon insulator.

[f] Localized attack of heat-affected zone of weld.

[g] Wear on edge of specimen due to movement of plastic balls.

[h] Edge of specimen damaged by impact of sharp object.

[i] Attack of weld.

[j] Evaluation: good, little or no change in condition of specimen; fair, definite change, probably could be used; poor, failed or severely damaged.

TABLE III

Corrosion Tests Conducted in the Hydro-Filter System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--Aug. 12, 1972, to Feb. [illegible], 1973; operating time--2203 hours or 91.8 days; and idle time--1950 hours or 81.3 days)

Corrosion specimens							
Exposed in	Inlet gas	Liquor and inlet gas	Gas and liquor	Exhaust gas (heated)	Effluent liquor	Recycle liquor	Liquor in clarifier
Locations (See Fig. 4), Reference No.	5002[a]	5006	5005	5007	5008	5012	5013
Gas							
Temperature, °F	120-150	95-135	95-130	235-265	-	-	-
Velocity, ft/sec	20-45	3-8	3-8	25-60	-	-	-
Flow rate, 1000's of actual ft^3/min	10-25	10-25	10-25	12.5-30	-	-	-
Composition, % by volume							
SO_2	0.3	0.1	0.1	0.1	-	-	-
CO_2	13	12	12	12	-	-	-
N_2	74	69	69	69	-	-	-
O_2	4.5	4	4	4	-	-	-
H_2O	8	15	15	15	-	-	-
Fly ash, gr/standard ft^3	3-5	0.02	0.02	0.02	-	-	-
Liquor							
Temperature, °F	-	-	-	-	75-125	75-125	75-100
Solids, % by weight	-	-	-	-	4-10	4-10	0-20
pH	-	-	-	-	5.6-6.4	5.3-6.4	6.1-7.4
Composition, % by weight							
$CaSO_4 \cdot 2H_2O$	-	-	-	-	1.0-2.0	1.0-2.0	0-4
$CaSO_3 \cdot 1/2H_2O$	-	-	-	-	1.5-3.5	1.5-3.5	0-7
Unreacted limestone plus fly ash	-	-	-	-	1.5-4.5	1.5-4.5	0-10
Water	-	-	-	-	90-96	90-96	80-100
Corrosion rate of metals[b], mils/yr							
Aluminum 5005, weld ER1100	> 160	P9	P18	5, -[c]	2, -[c]	< 1	P[illegible]
Carpenter 20Cb-3, weld Carpenter 20Cb-3	4, Pm	Neg.	Neg.	Pm	Neg.	Neg.	Neg.
Carpenter 20Cb-3, weld Carpenter 20Cb-3, stressed	-	-	< 1	< 1	< 1	-	-
Cor-Ten B, weld E8018-C3	> 300	40	13	4, -[c]	5, -[c]	10	7
Cupro-nickel 70-30, weld [illegible] RCuNi	35[d]	1	1	3	< 1	< 1	1
E-Brite 26-1, weld E-Brite 26-1	> 130	< 1, P1	Neg.	P7	Neg.	< 1	< 1
E-Brite 26-1, weld E-Brite 26-1, stressed	-	-	< 1, -[c]	< 1, P18	< 1	-	-
Hastelloy B, weld Hastelloy B	71	2	4	2	< 1	< 1	< 1
Hastelloy C-276, weld Hastelloy C-276	< 1	Neg.	Neg.	< 1	< 1	Neg.	< 1
Incoloy 800, weld Inconel 82	93	< 1, P19	< 1	1	< 1	Neg.	Neg.
Incoloy 825, weld Incoloy 65	2	Neg.	< 1	< 1	< 1	Neg.	< 1
Incoloy 825, weld Incoloy 65, stressed	-	-	< 1	1	< 1	-	-
Inconel 625, weld Inconel 625	< 1	Neg.	< 1	< 1, Pm	Neg.	Neg.	Neg.
Mild steel A-283, weld E6012	> 300	37	14	4, -[c]	4, -[c]	11	9
Monel 400, weld Monel 400	30, -[d]	< 1	2	3	< 1	< 1	< 1, -[c]
Type 304L, weld Type 308L	> 140	P12, -[c]	P10	1, Pm	< 1, -[c]	Neg.	< 1
Type 304L, weld Type 308L, stressed	-	-	P18, -[c]	< 1, Pm	P5, -[c]	-	-
Type 316L, weld Type 316L	G18, Pm	Neg.	Neg.	< 1	< 1	Neg.	Neg.
Type 316L, weld Type 316L stressed	-	-	< 1, -[c]	< 1, Pm	< 1	-	-
Type 410, weld Type 309	> 100	P8, -[c]	P3, -[c]	3, -[c]	Pm, -[c]	P7, -[c]	P16, -[c]
Type 446, weld Type 309	> 90	P9, -[c]	P10, -[c]	1, Pm	< 1, -[c]	-[c]	P9, -[c]
USS 18-18-2, weld Inconel 82	> 120	P8, -[c]	P9, -[c]	2	Pm, -[c]	< 1, -[c]	P5, -[c]
Evaluation of nonmetallic materials[e]							
Plastics							
Bondstrand 4000 (Fiber glass reinforced epoxy).	Poor	Good	Good[f]	Poor	Good	Good	P13, Poor
Flakeline 200 (Inert flakes and polyester resin).	Poor	Fair	Fair	Good	Fair	Fair	Fair
Qua-Corr (Fiber glass reinforced furan resin).	-	-	Good[f]	-	Good	-	-
Rubbers							
Butyl 26,666 (Copolymer of isobutylene-isoprene).	-	-	Good[f]	-	Good	-	-
Natural 1375 (Polyisoprene)	-	-	Good[f]	-	Good	-	-
Neoprene 9150 (Chloroprene polymer)	-	-	Good[f]	-	Good	-	-
Ceramic							
Transite (Portland cement and asbestos)	Poor	Fair	Good[f]	Good	Good	Good	Good

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[a] Spray water was used at all times at test point 5002 to humidify the gas.

[b] The "greater than" (>) sign is used when a specimen was completely destroyed. "P" preceding a number indicates pitting during the exposure period to the depth in mils shown by the number, and "Pm" indicates minute pits. "Neg.," negligible, no weight loss or localized attack. "G," groove of depth in mils shown.

[c] Crevice corrosion at Teflon insulator.

[d] Attack at weld.

[e] Evaluation: Good, little or no change in condition of specimen; fair, definite change, probably could be used; poor, failed or severely damaged.

[f] Specimen was damaged by impact of sharp instrument during the exposure period.

TABLE IV

Compositions of Alloys Tested in the Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

Alloys	Chemical analysis, %												
	C	Cr	Ni	Fe	Cu	Mo	Mn	Si	P	S	Al	Ti	Others
1. Aluminum 3003	-	-	-	0.7[a]	0.2[a]	-	1.0-1.5	0.6[a]	-	-	Bal.	-	Zn 0.1[a], Total 0.15
2. Carpenter 20Cb-3	0.07[a]	19-21	32-38	Bal.	3-4	2-3	2.00[a]	1.00[a]	0.035[a]	0.035[a]	-	-	Cb + Ta 8 x C
3. Cor-Ten B[b]	0.066	0.52	0.018	Bal.	0.31	0.010	1.20	0.29	0.012	0.031	0.056	-	V 0.05
4. Cupro-nickel 70-30[b]	-	-	31.00	0.53	67.79	-	0.52	-	0.003	0.005	-	-	Zn 0.034, Pb 0.002
5. E-Brite 26-1[b]	< 0.001	26.17	0.08	Bal.	0.01	1.00	0.01	0.19	0.010	0.012	-	-	N 0.010
6. Hastelloy B[b]	< 0.01	0.19	Bal.	5.75	-	26.20	0.58	0.01	0.005	0.006	-	-	Co 0.85, V 0.26
7. Hastelloy C-276[b]	0.002	15.87	Bal.	5.96	-	16.32	0.49	< 0.01	0.012	0.010	-	-	Co 1.84, W 3.51, V 0.25
8. Incoloy 800[b]	0.04	21.11	31.32	45.01	0.40	-	0.84	0.31	-	0.007	0.48	0.46	
9. Incoloy 825[b]	0.04	22.28	42.22	28.30	2.12	-	0.56	0.34	-	0.007	0.06	0.66	
10. Inconel 625	0.1[a]	20-23	Bal.	5.00[a]	-	8-10	0.5[a]	0.5[a]	0.015[a]	0.015[a]	0.4[a]	0.4[a]	Co 1.0[a], Cb + Ta 3.15 - 4.15
11. Mild Steel A-283[b]	0.17	-	-	Bal.	0.037	-	0.48	0.070	0.015	0.024	0.005	-	
12. Monel 400[b]	0.09	-	64.66	1.00	33.06	-	1.08	0.08	-	0.008	0.004	-	
13. Type 304L	0.030[a]	18-20	8-12	Bal.	-	-	2.00[a]	1.00[a]	0.045[a]	0.030[a]	-	-	
14. Type 316L	0.030[a]	16-18	10-14	Bal.	-	2.0-3.0	2.00[a]	1.00[a]	0.045[a]	0.030[a]	-	-	
15. Type 410[b]	0.062	12.7	0.16	Bal.	0.03	0.054	0.43	0.40	0.014	0.018	0.069	-	N 0.034, V < 0.05
16. Type 446[b]	0.10	24.6	0.50	Bal.	0.045	0.10	0.71	0.37	0.018	0.010	0.008	< 0.02	N 0.13, V < 0.05
17. USS 18-18-2[b]	0.065	18.2	18.0	Bal.	0.03	0.018	1.50	1.94	0.007	0.009	0.001	-	N 0.04

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[a] Maximum.

[b] Analysis was supplied with the material received for use in corrosion tests.

Table V

Analyses[a] of Deposits in Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

Identification of sample			Composition, % by weight								
			Scale or sludge deposit						Soot material[b]		
Date	Number	Location	CaO	SO_2	SO_3	CO_2	MgO	Others	Ash	H_2O	Hydrocarbon
Venturi System											
2/1/73	VD 2173	Scale from recirculation tank D-104.	25.4	9.0	37.3	1.3	-	25.5	-	-	-
2/23/73	VD 2 2373	Soot from gas duct about 25 feet above reheater.	-	-	-	-	-	-	56.0 (64.2)	12.8 -	31.2 (35.8)
TCA System											
2/3/73	TCA D 12373	Scale from recirculation tank D-204 (Test 2012).	31.2	10.4	28.7	6.3	-	23.4	-	-	-
2/3/73	TCA D 22373	Scale from spool of corrosion specimens (Test 2006)	28.5	17.6	27.4	0.5	-	25.9	-	-	-
2/5/73	TCA D 12573	Scale from scrubber wall below and near Koch tray.	39.7	16.8	25.9	2.0	0.22	15.4	-	-	-
2/5/73	TCA D 22573	Scale from grid-wall junction, elevation 396 feet 1-1/2 inches.	41.2	15.8	24.4	6.2	0.21	12.3	-	-	-
2/22/73	TCA D 122273	Rust-colored scale from corroded demister.	3.6	4.2	83.2	0.0	-	9.0	-	-	-
2/12/73	TCA D 121273	Tar-like material from duct 25 feet downstream from reheater.	-	-	-	-	-	-	25.2 (27.3)	7.8 -	67.0 (72.7)
2/12/73	TCA D 221273	Tar-like material downstream from and near reheater.	-	-	-	-	-	-	39.3 (40.0)	1.7 -	59.0 (60.0)
Hydro-Filter System											
2/2/73	HFD-2273	Scale from corrosion spool above marble bed.	29.5	17.6	27.4	0.5	-	24.9	-	-	-
2/8/73	HFD-2373	Deposit from bottom slurry nozzle.	28.8	9.6	41.7	2.2	-	17.7	-	-	-
2/23/73	HFD-22373	Soot from gas duct about 25 feet above reheater.	-	-	-	-	-	-	36.4 (41.2)	11.7 -	51.9 (58.8)
General Operation Equipment											
3/1/73	3173	Scale from reslurry pump G-401.	39.3	0.54	12.8	20.1	-	26.7	-	-	-

---

[a] Information taken from reports dated March and May 1973 by R. E. Wagner of inspections made February 1, 2, and 3, 1973 of the Hydro-Filter, the venturi, and the TCA scrubber systems.

[b] Values in parentheses are on a dry basis.

TABLE VI

Hardness of Neoprene Linings of Equipment in the Three Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack One at Shawnee Power Plant

(Exposure period: Aug. 12, 1972, to Feb. 5, 1973)

Reproduced from best available copy.

Location of hardness test	Test temp., °F[a]	Durometer "A" hardness Original[b]	Final[c]
Venturi System (1840 Operating Hours)			
Afterscrubber Tower:			
Eight inches below Type 316L stainless steel at venturi section	-	60 to 65	67
Above trapout tray (approximate elevation 388 feet)	-	60 to 65	53 to 60
Three inches below mist eliminator	-	60 to 65	54 to 60
Three feet above mist eliminator	-	60 to 65	53 to 55
Four inches below Type 316L stainless steel duct to reheater	-	60 to 65	52 to 54
Clarified Process Water Storage Tank, D-105:			
Above liquid level	60	55 to 60	64 to 65
Below liquid level	60	55 to 60	61 to 63
Recirculation Tank:			
Five feet above bottom	-	55 to 60	65 to 69
Blades of agitator	-	60 to 70	63 to 67
Blades of Agitator In:			
Effluent hold tank D-101	-	60 to 70	65 to 66
Recirculation tank D-104	-	60 to 70	63 to 67
Pumps G-101, G-102, G-103, and G-104:			
Impellers and casings	-	54 to 56	60 to 70
New impellers and casings (spares)	-	-	64 to 72
TCA System ([illegible] Operating Hours)			
Scrubber Tower:			
Middle of wall and 6 inches below manway	-	60 to 65	55
Six inches above bottom grid (four walls)	60	60 to 65	58 to 60
Three feet above bottom grid near test spool 2006	-	60 to 65	59 to 63
Four feet below Koch tray	-	60 to 65	59 to 60
Two feet above Koch tray	-	60 to 65	53 to 55
Clarified Process Water Storage Tank, D-203:			
Above liquid level	60	55 to 60	62 to 71
Below liquid level	60	55 to 60	64 to 70
Recirculation Tank, D-204:			
Four and one-half feet above bottom	40	55 to 60	60 to 66
Blades of agitator	40	60 to 70	54 to 56
Blades of Agitator In:			
Effluent hold tank D-201	40	60 to 70	71
Recirculation tank D-204	-	60 to 70	54 to 58
Pumps G-201, G-202, and G-204:			
Impellers and casings	-	54 to 56	61 to 68
Hydro-Filter System ([illegible] Operating Hours)			
Scrubber Tower:			
Five inches below marble bed	36	60 to 65	68 to 72
Six inches above marble bed	36	60 to 65	70 to 71
Above demister and 6 inches below reducer	36	60 to 65	64 to 67
Three inches below Type 316L stainless steel stack	36	60 to 65	63 to 70
Clarified Process Water Storage Tank, D-303:			
Above liquid level	60	55 to 60	60 to 61
Below liquid level	60	55 to 60	58 to 60
Recirculation Tank, D-304:			
Five feet above bottom	-	55 to 60	75 to 80
Blades of agitator	-	60 to 70	67 to 70
Blades of Agitator In:			
Effluent hold tank D-301	40	60 to 70	63 to 66
Recirculation tank D-304	-	60 to 70	67 to 70
Pumps G-301, G-303A, G-303B, and G-304:			
Impellers and casings	35	54 to 56	52 to 68

---

[a] Atmospheric temperature varied from about 35° to 60°F while tests for hardness were being made.

[b] Values not determined by TVA but were taken from information supplied to contractors for bidding on construction.

[c] The instrument used to determine the durometer hardness of neoprene linings during inspection of the plants (Feb. 1-5, 1973) was Shore "A-2," ASTM D2240. Note that the measurements were made over a wide range of temperatures; therefore, an exact comparison of hardness values is not possible. Usually three or more tests were made in an area.

TABLE VII

Hardness[a] of Rubber Lining[b] Specimens Tested in the Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Exposure period—Aug. 12, 1972, to Feb. 3, 1973)

Location of specimens[c]	Durometer "A" hardness Butyl (26,666)	Natural (1375)	Neoprene (9150)
As received	54–56 (55)	34–37 (35)	64–65 (64)
Venturi System (1840 Operating Hours)			
1008	56–58 (57)	39–40 (40)	60–63 (61)
1011	54–58 (56)	41–43 (42)	62–63 (62)
TCA System (1667 Operating Hours)			
2004	56–59 (57)	38–42 (40)	59–61 (60)
2008	54–58 (56)	36–39 (38)	59–64 (62)
Hydro-Filter System (2203 Operating Hours)			
3005	55–58 (57)	35–39 (38)	58–62 (60)
3008	54–58 (56)	37–40 (38)	61–65 (63)

---

[a] Four tests were made of each specimen in the laboratory at 78°F with a durometer type "A2," ASTM D2240, manufactured by The Shore Instrument and Manufacturing Company. Values in parentheses are averages.

[b] Specimens of butyl, natural, and neoprene liners were applied on mild steel coupons by the Gates Rubber Company.

[c] See reference numbers on Figures 2–4.

TABLE VIII

Compilation of Corrosion Data of Materials Tested in the Three Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

			Corrosion[a]						
Metals[d]	Cost comparison[b]		On basis of weight loss, mils/yr, range	Specimens pitted			Specimens with crevice attack, No.	Specimens with other types of attack	
	A	B		No.	Depth, mils[c]			No.	Area
					Minimum	Maximum			
1. Hastelloy C-276	9.29	-	Neg. to 5	-	-	-	-	-	-
2. Inconel 625	6.59[e]	6.05	Neg. to 5	1	-	Minute	-	-	-
3. Incoloy 825	4.46[f]	3.73	Neg. to 7	-	-	-	1	-	-
4. Carpenter 20Cb-3	4.21	3.73	Neg. to 14	2	-	Minute	-	-	-
5. Type 316L SS	1.39	1.61	Neg. to 15	3	-	Minute	2	1, 1	G18[g], weld
6. Cupro-nickel 70-30	1.80[f]	-	< 1 to 49	1	-	18	-	1	Weld
7. Monel 400	2.93[f]	3.61	< 1 to 57	1	-	2	1	3	Weld
8. Hastelloy B	9.47	-	< 1 to 100	2	-	Minute	-	-	-
9. Type 446 SS	-	-	Neg. to 140	9	Minute	19	11	-	-
10. E-Brite 26-1	-	1.85	Neg. to 190	10	Minute	18	2	-	-
11. Incoloy 800	2.54	2.70	Neg. to 190	6	Minute	19	3	1	-[h]
12. USS 18-18-2	-	-	Neg. to 200	11	Minute	16	11	-	-
13. Type 304L SS	1.11	1.11	Neg. to 200	14	Minute	23	11	1	-[h]
14. Type 410 SS	1.92	0.93	< 1 to > 250	15	Minute	16	16	-	-
15. Aluminum 3003	-	-	< 1 to > 550	9	2	70	5	-	-
16. Mild Steel A-283	0.34[e], 0.80[f]	-	< 1 to > 1400	2	-	Minute	2	-	-
17. Cor-Ten B	-	-	< 1 to > 1400	5	Minute	3	4	1	Weld

	Condition		
Nonmetallic Materials	Good	Fair	Poor
Plastics			
1. Bondstrand 4000	12	-	9
2. Flakeline 200	2	14	5
3. Qua-Corr	5	-	1
Rubbers			
1. Butyl 26,666	6	-	-
2. Natural 1375	6	-	-
3. Neoprene 9150	6	-	-
Ceramic			
1. Transite	14	2	5

---

[a] The compilation is based on 21 tests of each material except for Qua-Corr and the three rubbers (butyl, natural, and neoprene) with which only six tests were conducted.

[b] Cost comparison values are based on Type 304 stainless steel having a value of 1.00. "A" is based on commercial quality tubing--10,000 feet of 3/4-inch outside diameter by 0.065-inch average wall which is cut to 20-foot 0-inch lengths. /Information from Carpenter Technology Corporation (August 7, 1973)./ "B" is based on 1/8-inch sheet in 20,000-pound lots. /Information from J. M. Tull, Atlanta, Georgia, by telephone (July 2, 1973)./

[c] The actual depth of penetration in mils during exposure periods is indicated in Tables I, II, and III.

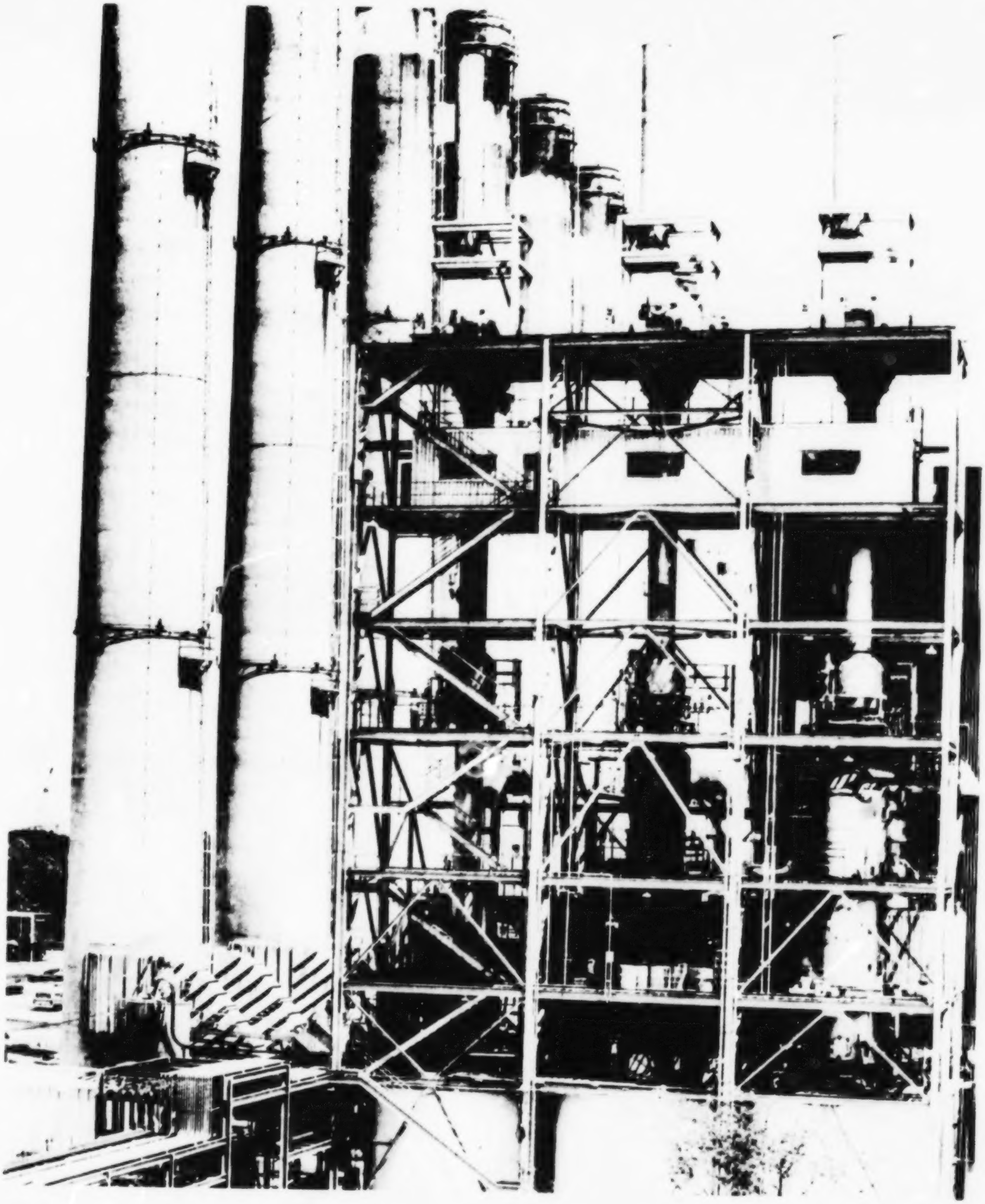
[d] Metals are listed in their approximate order of decreasing corrosion resistance.

[e] Welded.

[f] Seamless.

[g] A groove in parent metal was 18 mils deep.

[h] Severe localized attack of parent metal.



HYDRO-FILTER (FLOODED-BED OF MARBLES)
TCA (MOBILE BED OF PING-PONG BALLS)
VENTURI (FOLLOWED BY AFTER-SCRUBBER)

FIGURE I
THREE PARALLEL SYSTEMS OF LIMESTONE-WET-SCRUBBING TEST FACILITY AT SHAWNEE POWER PLANT

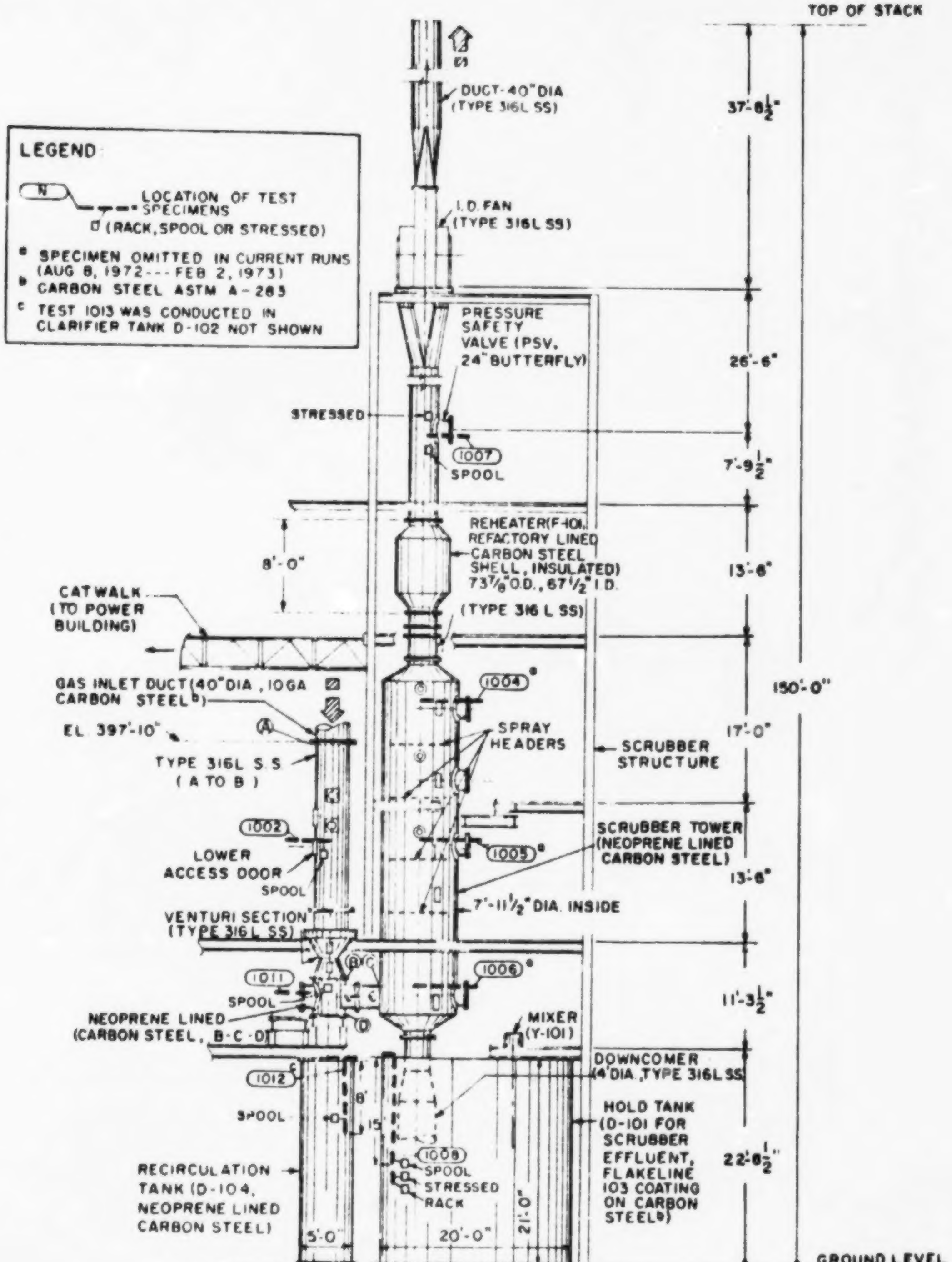

TOP OF STACK
DUCT-40" DIA (TYPE 316L SS)
37'-8½"
LEGEND
LOCATION OF TEST SPECIMENS
□ (RACK, SPOOL OR STRESSED)
a SPECIMEN OMITTED IN CURRENT RUNS (AUG 8, 1972--- FEB 2, 1973)
b CARBON STEEL ASTM A-283
c TEST 1013 WAS CONDUCTED IN CLARIFIER TANK D-102 NOT SHOWN
I.D. FAN (TYPE 316L SS)
PRESSURE SAFETY VALVE (PSV, 24" BUTTERFLY)
26'-6"
STRESSED
1007
SPOOL
7'-9½"
REHEATER (F-101, REFACTORY LINED CARBON STEEL SHELL, INSULATED) 73⅞" O.D., 67½" I.D.
8'-0"
13'-6"
CATWALK (TO POWER BUILDING)
(TYPE 316 L SS)
GAS INLET DUCT (40" DIA, 10GA CARBON STEEL b)
1004 a
EL. 397'-10"
A
SPRAY HEADERS
SCRUBBER STRUCTURE
17'-0"
150'-0"
TYPE 316L S.S (A TO B)
1002
LOWER ACCESS DOOR
SPOOL
SCRUBBER TOWER (NEOPRENE LINED CARBON STEEL)
1005 a
13'-6"
VENTURI SECTION (TYPE 316L SS)
7'-11½" DIA. INSIDE
B
C
1011
SPOOL
1006 a
11'-3½"
NEOPRENE LINED (CARBON STEEL, B-C-D)
D
MIXER (Y-101)
DOWNCOMER (4' DIA, TYPE 316L SS)
1012 c
8'
SPOOL
15'
1008
SPOOL
STRESSED
RACK
HOLD TANK (D-101 FOR SCRUBBER EFFLUENT, FLAKELINE 103 COATING ON CARBON STEEL b)
22'-8½"
RECIRCULATION TANK (D-104, NEOPRENE LINED CARBON STEEL)
5'-0"
20'-0"
21'-0"
GROUND LEVEL EL. 345'-0"

FIGURE 2
VENTURI SCRUBBER SYSTEM, (C-101)

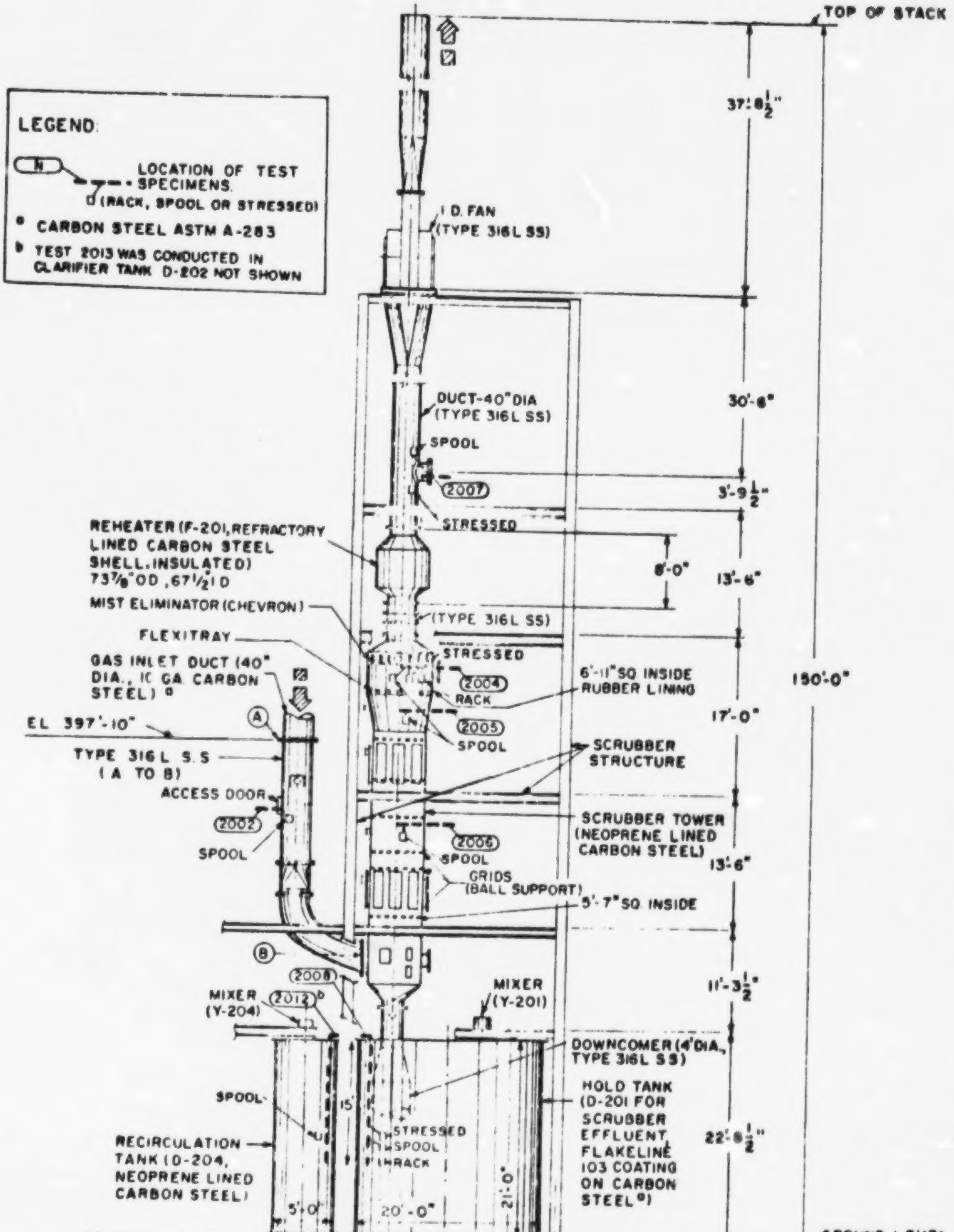

LEGEND:
N
LOCATION OF TEST SPECIMENS
(RACK, SPOOL OR STRESSED)
a CARBON STEEL ASTM A-283
b TEST 2013 WAS CONDUCTED IN CLARIFIER TANK D-202 NOT SHOWN
TOP OF STACK
37'-8 1/2"
I.D. FAN (TYPE 316L SS)
DUCT-40" DIA (TYPE 316L SS)
SPOOL
2007
30'-6"
3'-9 1/2"
STRESSED
REHEATER (F-201, REFRACTORY LINED CARBON STEEL SHELL, INSULATED) 73 7/8" OD, 67 1/2" I D
8'-0"
13'-6"
MIST ELIMINATOR (CHEVRON)
(TYPE 316L SS)
FLEXITRAY
STRESSED
GAS INLET DUCT (40" DIA., 10 GA. CARBON STEEL) a
2004
RACK
6'-11" SQ INSIDE RUBBER LINING
150'-0"
A
EL 397'-10"
2005
SPOOL
17'-0"
TYPE 316L S.S (A TO B)
SCRUBBER STRUCTURE
ACCESS DOOR
2002
SPOOL
SCRUBBER TOWER (NEOPRENE LINED CARBON STEEL)
2006
SPOOL
13'-6"
GRIDS (BALL SUPPORT)
5'-7" SQ INSIDE
B
2008
MIXER (Y-204)
2012 b
MIXER (Y-201)
11'-3 1/2"
DOWNCOMER (4' DIA, TYPE 316L SS)
SPOOL
15'
STRESSED
SPOOL
RACK
RECIRCULATION TANK (D-204, NEOPRENE LINED CARBON STEEL)
HOLD TANK (D-201 FOR SCRUBBER EFFLUENT, FLAKELINE 103 COATING ON CARBON STEEL a)
22'-8 1/2"
21'-0"
5'-0"
20'-0"
GROUND LEVEL EL. 345'-0"

FIGURE 3
TURBULENT CONTACT SCRUBBER SYSTEM, TCA-(C-201)
(MOBILE BED, -- PING-PONG BALL)

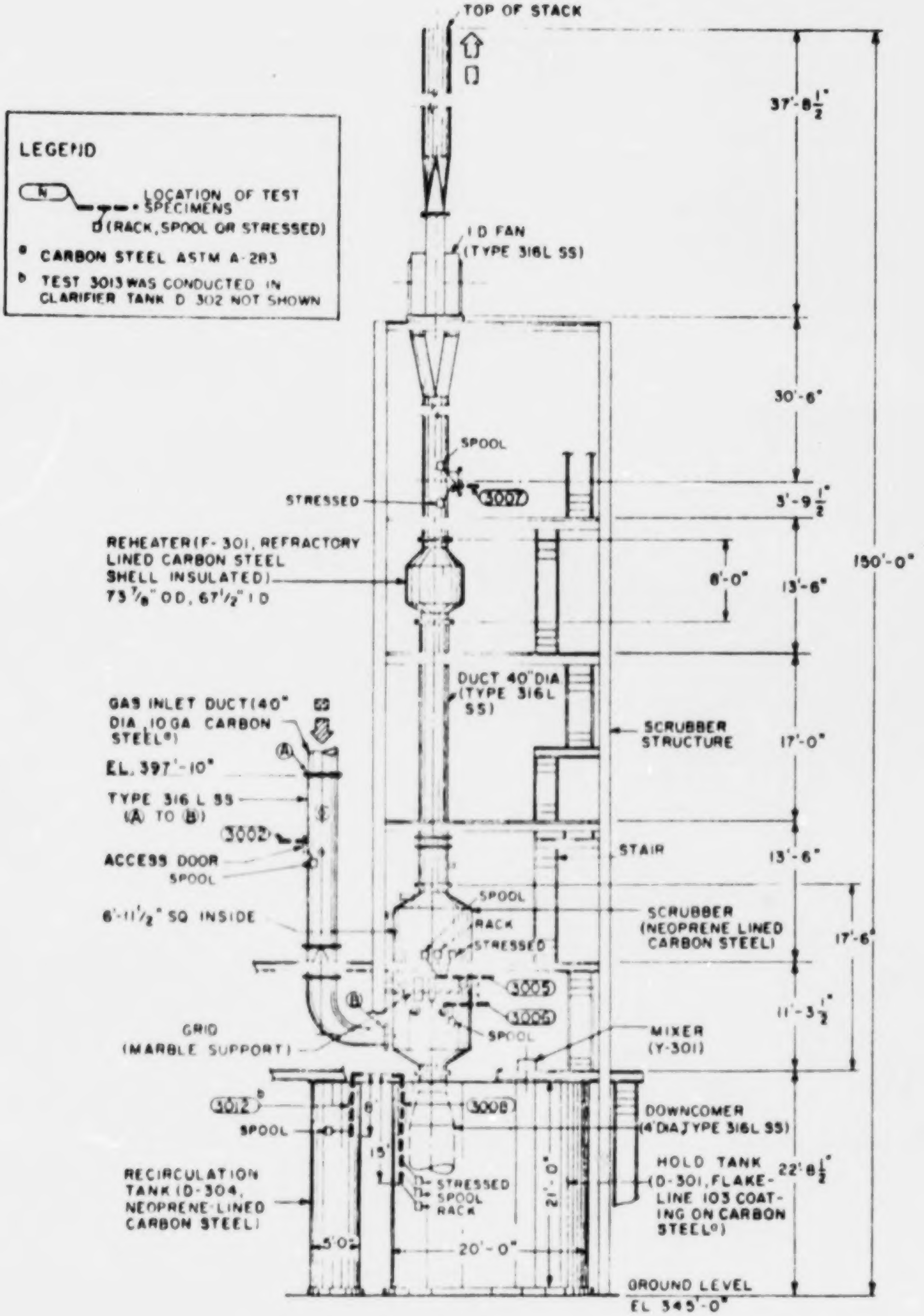

LEGEND
N
LOCATION OF TEST SPECIMENS
(RACK, SPOOL OR STRESSED)
a CARBON STEEL ASTM A-283
b TEST 3013 WAS CONDUCTED IN CLARIFIER TANK D 302 NOT SHOWN
TOP OF STACK
I D FAN (TYPE 316L SS)
37'-8 1/2"
30'-6"
SPOOL
STRESSED
3007
5'-9 1/2"
150'-0"
REHEATER (F-301, REFRACTORY LINED CARBON STEEL SHELL INSULATED) 73 7/8" OD, 67 1/2" ID
8'-0"
13'-6"
DUCT 40" DIA (TYPE 316L SS)
GAS INLET DUCT (40" DIA, 10 GA CARBON STEEL a)
A
EL. 397'-10"
SCRUBBER STRUCTURE
17'-0"
TYPE 316 L SS (A TO B)
3002
ACCESS DOOR
SPOOL
STAIR
13'-6"
6'-11 1/2" SQ INSIDE
SPOOL
RACK
STRESSED
SCRUBBER (NEOPRENE LINED CARBON STEEL)
17'-6"
B
3005
3006
11'-3 1/2"
GRID (MARBLE SUPPORT)
SPOOL
MIXER (Y-301)
3012 b
SPOOL
6'
15'
3008
DOWNCOMER (4' DIA TYPE 316L SS)
STRESSED
SPOOL
RACK
RECIRCULATION TANK (D-304, NEOPRENE-LINED CARBON STEEL)
21'-0"
HOLD TANK (D-301, FLAKE-LINE 103 COATING ON CARBON STEEL a)
22'-8 1/2"
5'-0"
20'-0"
GROUND LEVEL
EL 345'-0"

FIGURE 4
HYDRO-FILTER SCRUBBER SYSTEM, HF-(C-301)
(FLOODED BED OF MARBLES)

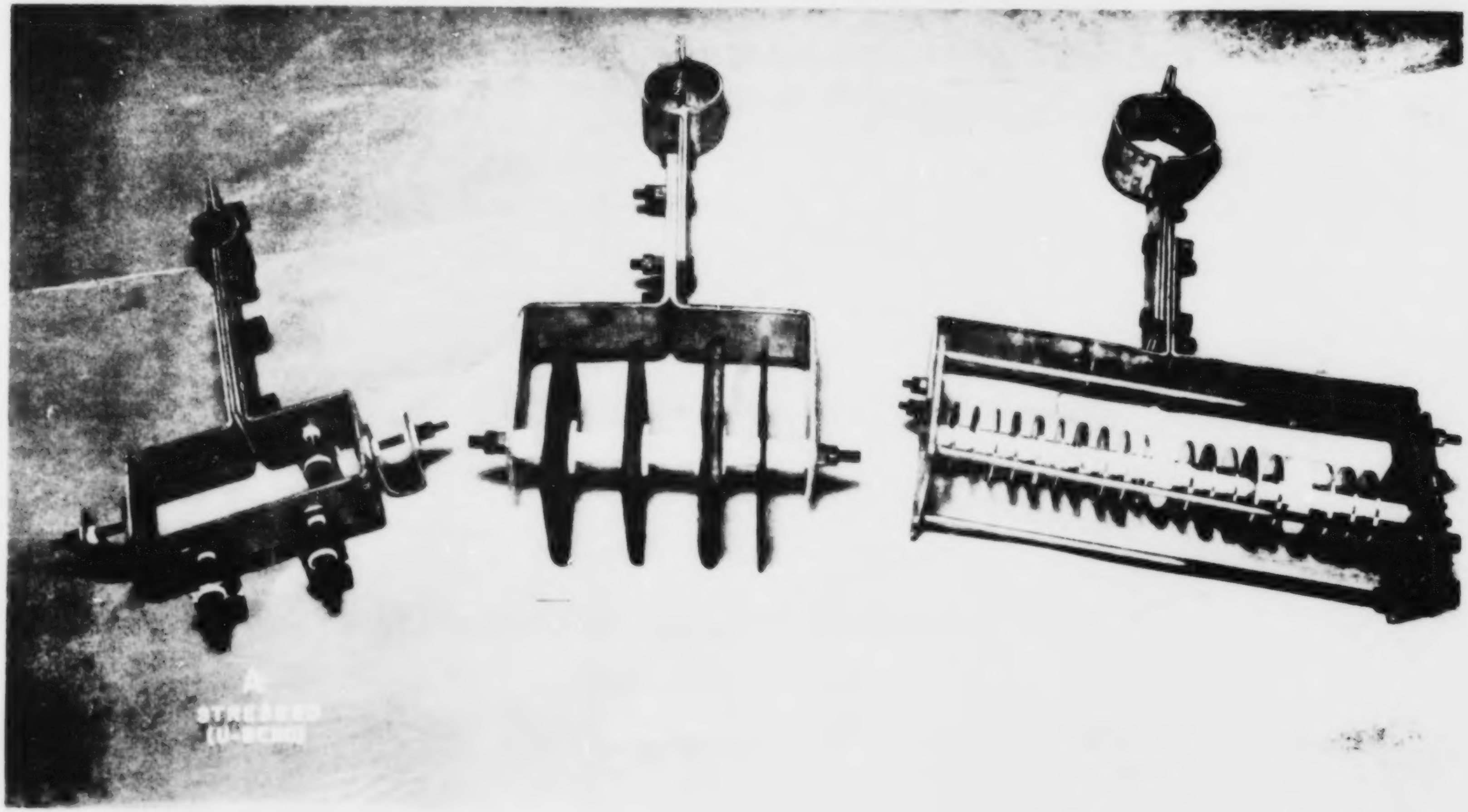


FIGURE 5
TYPICAL ASSEMBLIES OF CORROSION TEST SPECIMENS

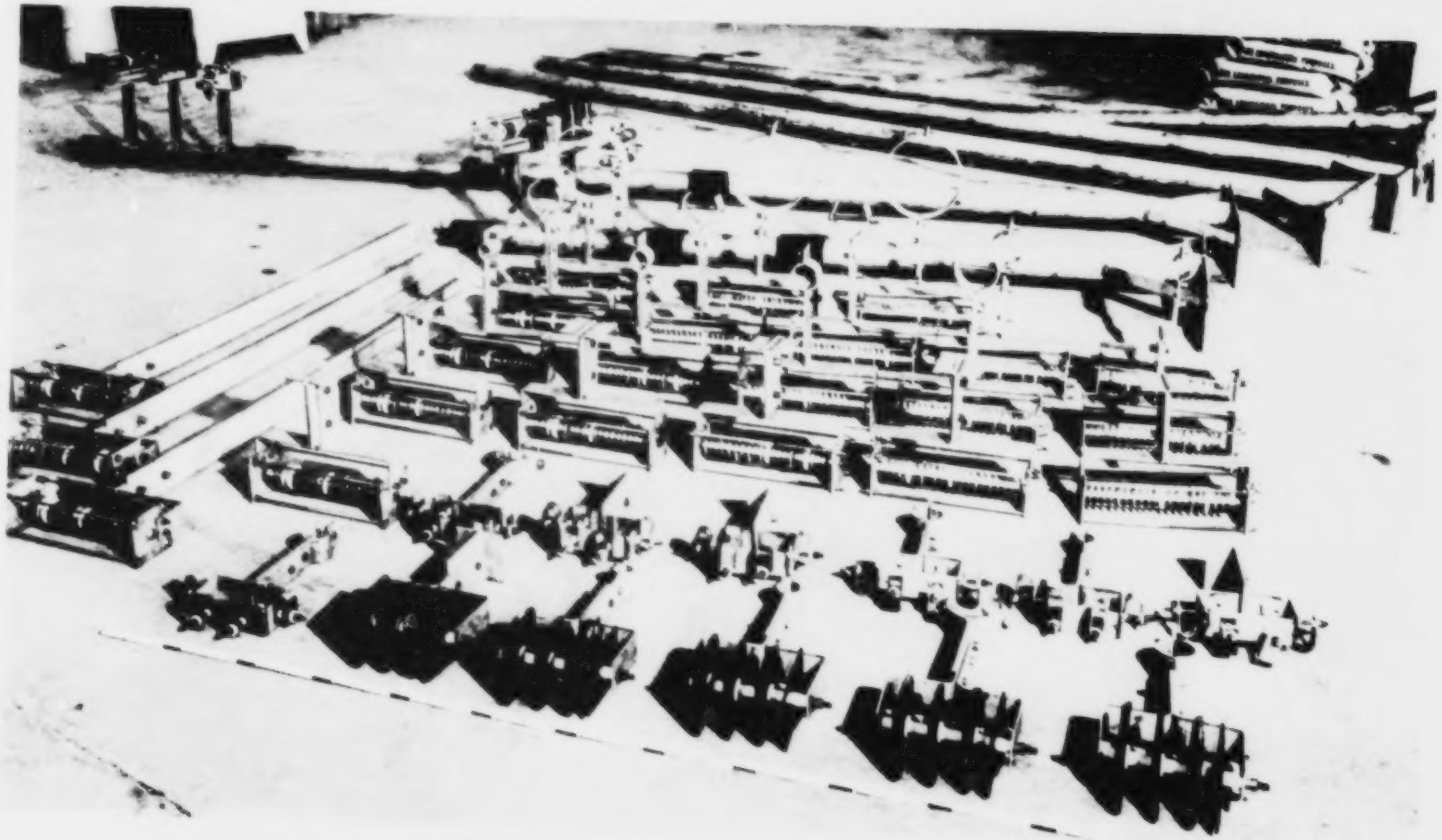


FIGURE 6
CORROSION TEST ASSEMBLIES AND SUPPORTS READY FOR INSTALLATION IN PLANTS

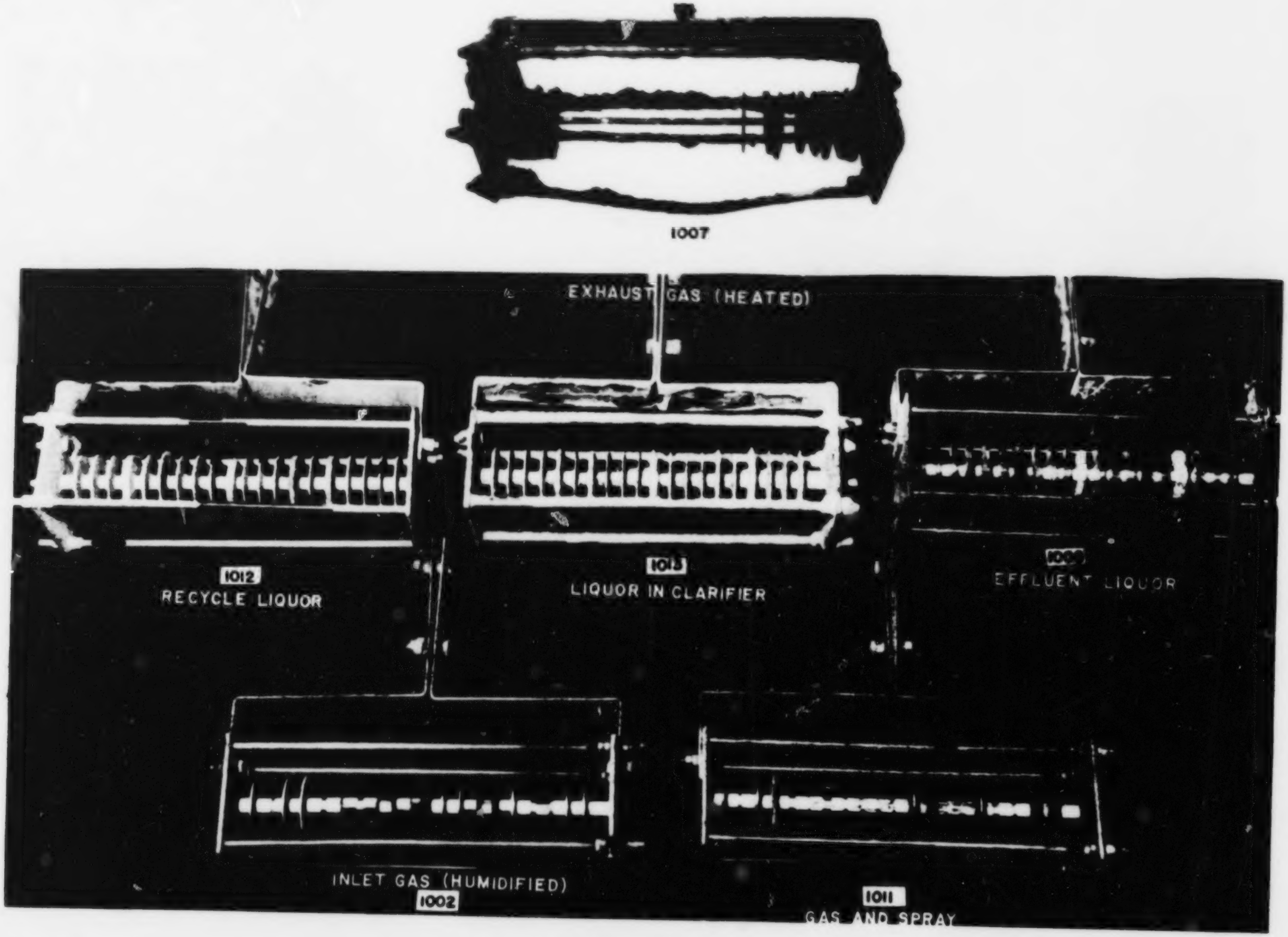


FIGURE 7
DISK SPECIMENS AFTER EXPOSURE IN VENTURI SYSTEM (AUG. 12, 1972--FEB. 2, 1973)

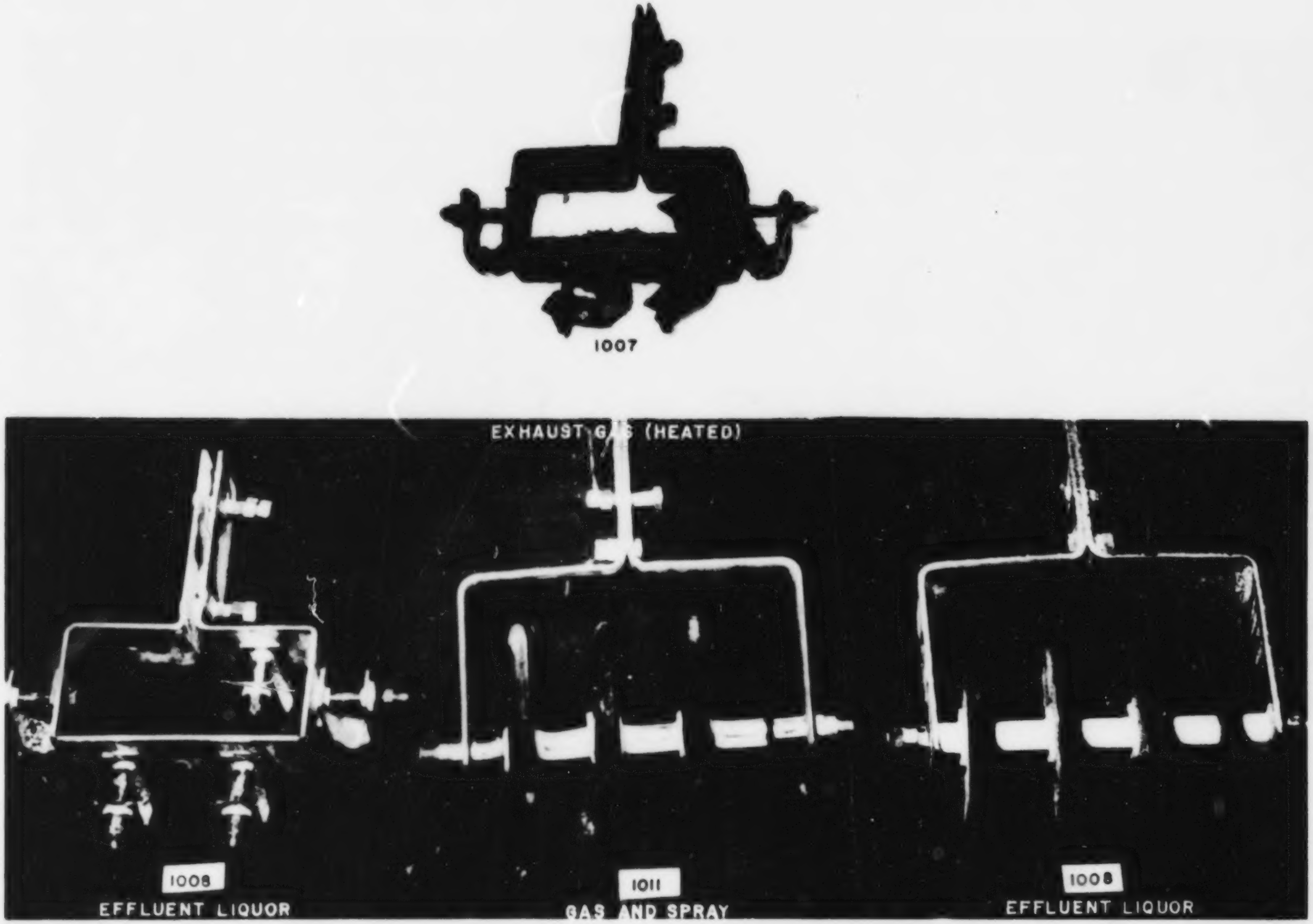


FIGURE 8
STRESSED AND COATED SPECIMENS AFTER EXPOSURE IN VENTURI SYSTEM
AUG. 12, 1972 - FEB. 2, 1973

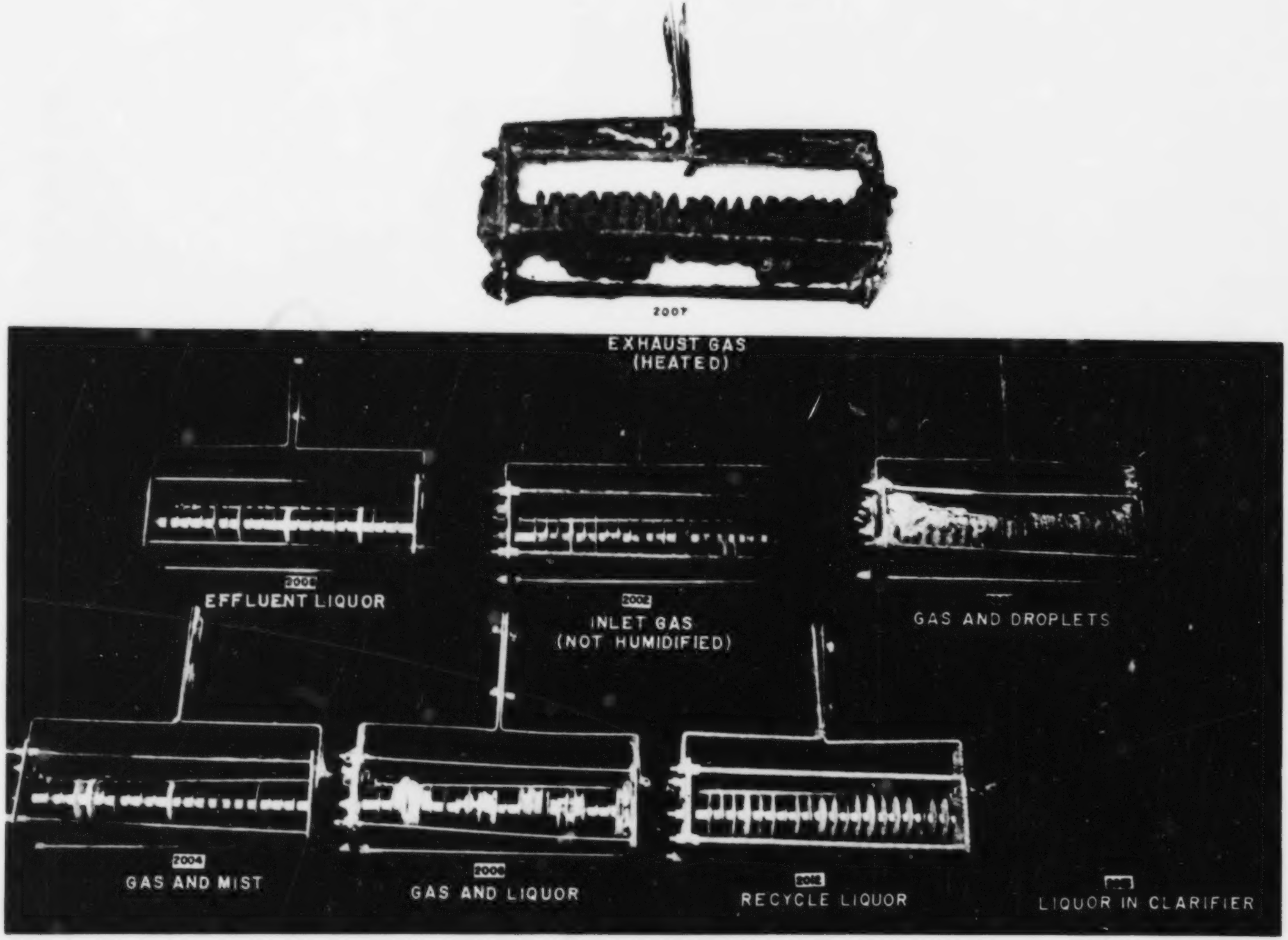


FIGURE 9
DISK SPECIMENS AFTER EXPOSURE IN TCA SYSTEM (AUG. 12, 1972--FEB. 3, 1973)

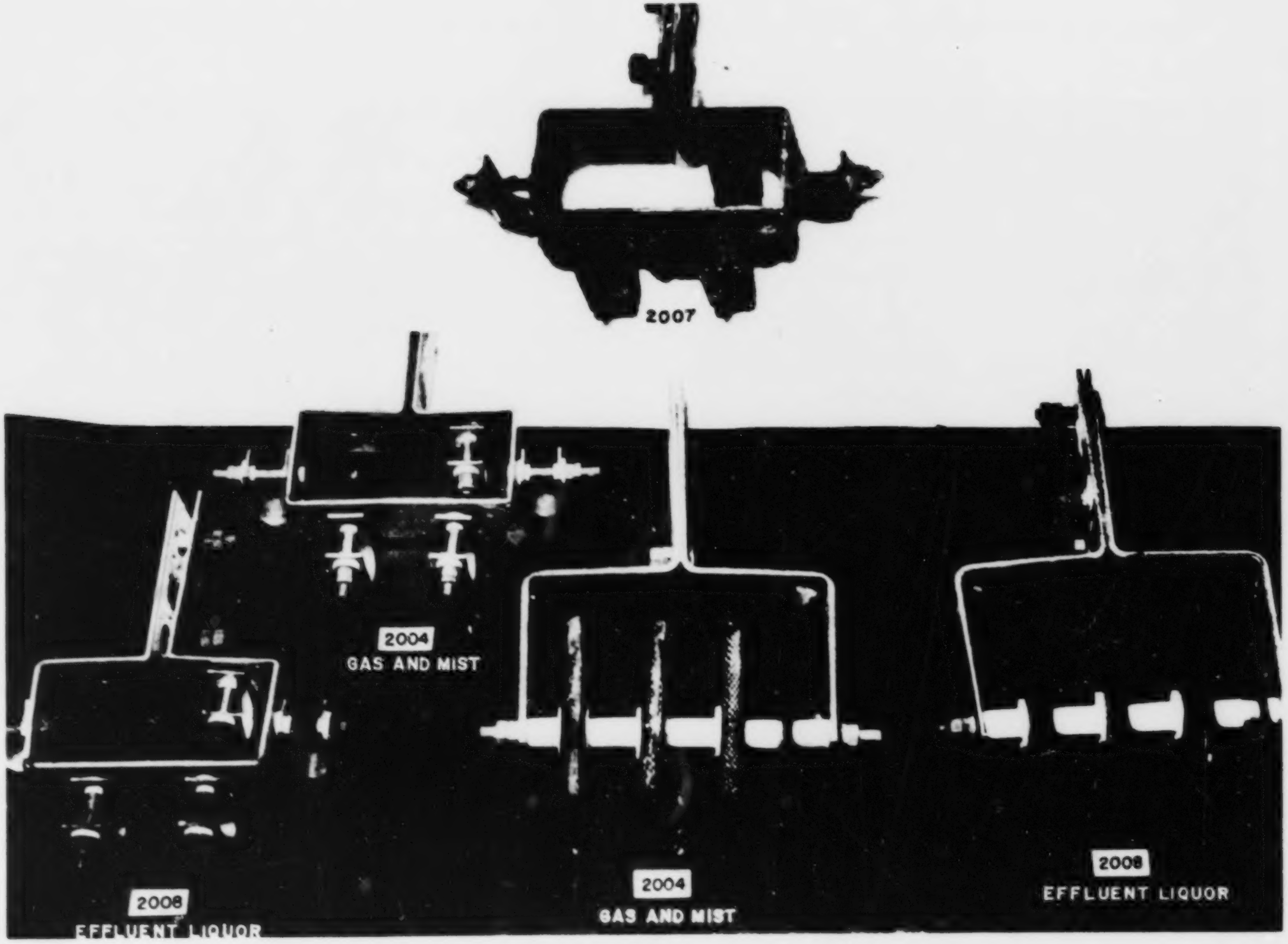


FIGURE 10
STRESSED AND COATED SPECIMENS AFTER EXPOSURE IN TCA SYSTEM
AUG. 12, 1972--FEB. 3, 1973

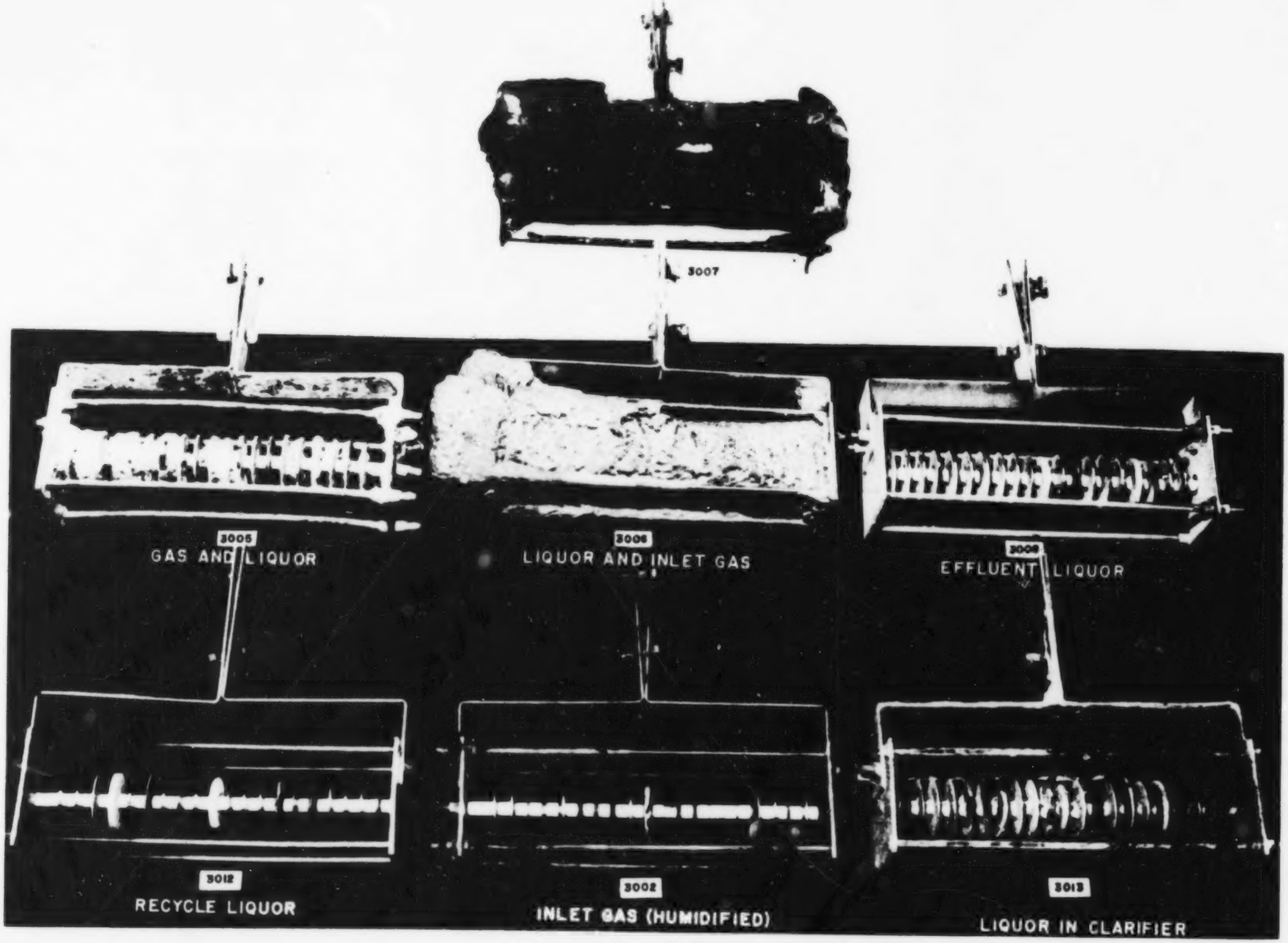


FIGURE 11
DISK SPECIMENS AFTER EXPOSURE IN HYDRO-FILTER SYSTEM (AUG. 12, 1972--FEB. 1, 1973)

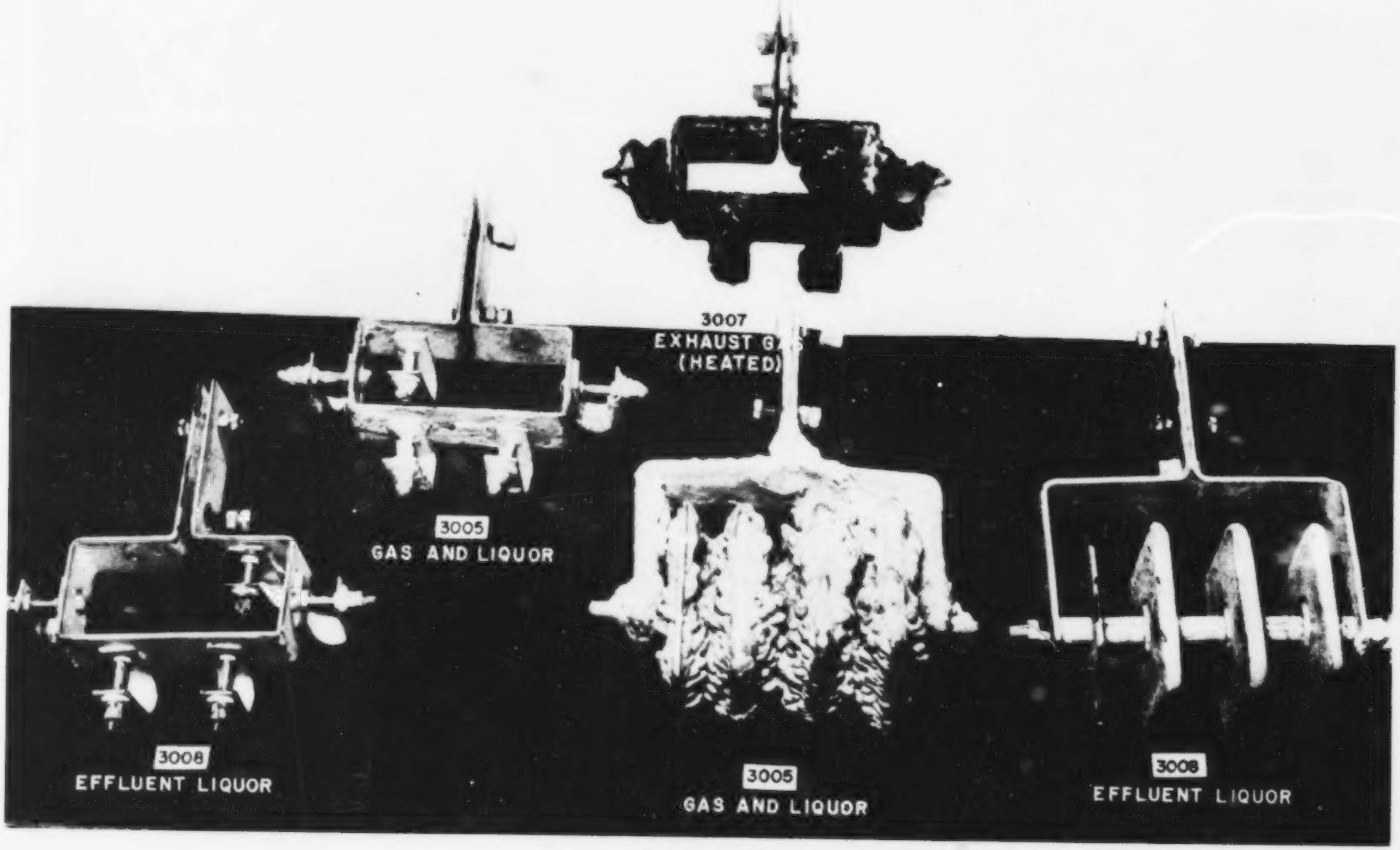


FIGURE 12
STRESSED AND COATED SPECIMENS AFTER EXPOSURE IN HYDRO-FILTER SYSTEM
AUG. 12, 1972--FEB. 1, 1973

Appendix K

SECOND TVA INTERIM REPORT OF CORROSION STUDIES: EPA ALKALI SCRUBBING TEST FACILITY

by

G. L. Crow
H. R. Horsman

May 1974

EPA ALKALI-SCRUBBING TEST FACILITY--SHAWNEE POWER PLANT

Second Interim Report of Corrosion Studies

The first interim report of corrosion tests conducted at the EPA alkali-scrubbing test facility at the Shawnee Power Plant was completed October 1, 1973. That report covered tests conducted during the period August 8, 1972, to February 3, 1973.

The current report gives results of the second series of tests. These tests were conducted during the period June 5 to September 16, 1973.

Results from the two series of tests and from inspections of equipment were comparable in most respects; however, comparisons of corrosion resistance of materials were more difficult to make in the second series of tests because the spools of specimens were not identical. Hastelloy C-276 and Inconel 625 showed good resistance to corrosion at all test locations in both series. Corrosion of Type 316L stainless steel on the basis of weight loss was moderate (< 1 to 7 mils/yr), but localized attack was prevalent, especially under deposits of solids. Armco 22-13-5 tested only in the second series (at nine locations) was highly resistant to general and to localized attack. Neoprene-lined towers, tanks, and pipelines were in good condition; however, several neoprene-lined centrifugal pumps were damaged and wear was apparent on the leading edge of neoprene-covered agitator blades. The polyester inert flake material used for lining several tanks was in good condition except for minor cracks. Corrosion tests are being continued.

Program and Facilities

Program: The experimental program for removing sulfur dioxide and particulate from stack gas at the coal-fired Shawnee Power Plant is a cooperative effort among the Environmental Protection Agency (EPA), Bechtel Corporation, and TVA. The limestone - wet-scrubbing program for sulfur dioxide removal is funded and directed by EPA. The Bechtel Corporation designed the plant facility and TVA built it. TVA is operating the plant under a test program developed and directed by Bechtel. Identification and solution of corrosion and erosion problems associated with construction materials are important goals in a program for the design and evaluation of limestone - wet-scrubbing systems. At the request of EPA in 1972, the Process Engineering Branch of TVA started corrosion tests in the three scrubber systems.

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Plant Facility: Much of the information about plant equipment, process flow, and preparation of corrosion test specimens was given in the report on the first series of tests but is repeated here for convenience.

The test facility at Shawnee consists of three parallel scrubber systems: (1) a venturi followed by a spray tower, (2) a Turbulent Contact Absorber (TCA), and (3) a marble-bed absorber. Each of these systems has the capacity to treat 30,000 acfm of gas containing 1800 to 4000 ppm of sulfur dioxide and 2 to 5 grains per standard cubic foot of particulates. Figures 1, 2, and 3 are schematic views of the venturi, TCA, and marble-bed scrubbing systems.

Power plant stack gas at an average temperature of 320°F (300°-350°F) flows through a 40-inch duct to a system where it is sprayed for humidification and for cooling. It then passes through limestone slurry in a particular type of test scrubber for sulfur dioxide removal. Afterward, it is passed through a mist eliminator, reheated to between 235° and 265°F to vaporize any residual mist and eliminate a plume, and discharged through a fan and duct to the atmosphere. Scrubber effluent is clarified to remove solids which are discarded and the liquor is then recirculated.

Some features common to all the systems are described below. A 40-inch duct is used to carry the stack gas at 320°F from the No. 10 boiler of the power plant to a test system; each duct is made of 10-gage carbon steel, ASTM A-283, and is insulated. The 40-inch duct connects to another gas duct made of Type 316L stainless steel. This duct is equipped with two sets of spray nozzles (the first for humidifying and the second for cooling the gas) and an air-operated soot blower. Downstream from each sulfur dioxide absorber and mist eliminator unit there are a stainless steel duct, a refractory-lined reheater fired with fuel oil, an induced-draft fan of stainless steel, and a stack of stainless steel. For liquor handling there are a slurry recirculation tank, a scrubber effluent tank, and a liquor clarification system. The effluent hold tank and a clarifier tank are made of carbon steel A-283 and coated inside with Flakeline 103 which is a Bisphenol polyester resin-fiber glass coating manufactured by the Ceilcote Company. The recirculation tank, clarified water storage tank, and reslurry tank are made of carbon steel and lined with neoprene.

Distinguishing features of the systems are as follows. In the venturi scrubber system shown in Figure 1, the gas is scrubbed in a venturi unit made of Type 316L stainless steel and then passed through a neoprene-lined spray tower (afterscrubber) with a chevron-type separator in the top for removal of mist. In the TCA system, shown in Figure 2, gas is scrubbed in a mobile bed of wetted balls, and the mist is removed in a wash tray and chevron-type separator in a tower lined with neoprene. In the marble-bed system shown in Figure 3, gas is scrubbed in a flooded bed of marbles, and the mist is removed in a chevron-type mist eliminator in a neoprene-lined scrubber tower.

Current Corrosion Tests

The second series of corrosion tests was conducted during the period June 5 to September 16, 1973. Only spools containing 2-inch disks were exposed in the second series. Eight spools of specimens were tested in the venturi system, 8 in the TCA, and 7 in the marble bed. Twenty-two alloys and 6 nonmetals were tested, but all materials were not exposed at the 23 test locations. Alloys that showed poor resistance to attack at some locations in the first series of tests were not retested at every location in the second series of tests. Stressed specimens were not included in the current tests.

Tables I, II, and III list the materials tested and identify the filler metal used in preparing welded specimens of the alloys. Alloys not included in the first series of tests but were added in the current tests follow: Armco 22-13-5, red brass, Crucible 26-1, and Types 201 and 317 stainless steel. The nonmetallic materials added in the second series of tests were Lucoflex (PVC), polyethylene Type III, and polypropylene. Test specimens of butyl, natural, and neoprene rubbers were not included in the current tests; these materials showed good resistance to attack in the previous tests.

Preparations for Corrosion Tests

Disks: Disk-type specimens, 2 inches in diameter, were prepared from the 22 metals. A weld was made (according to manufacturer's recommendations) across the diameter, and after being welded, the metal was cooled slowly in still air to simulate conditions of constructing or of repairing large equipment. Whenever it was available, metal stock of 1/8-inch minimum thickness was used, and the surfaces were machined smooth after the welding. Some alloys available only in thinner gages could not be machined, so the weld beads were smoothed by grinding. A hole, 23/64 inch in diameter, was drilled in the center of each disk for mounting.

Specimens of six nonmetallic materials, Bondstrand 4000, Flakeline 200, Lucoflex (PVC), polyethylene, polypropylene, and Transite, were also prepared as 2-inch disks and mounted on spools along with the metal disks. Flakeline 200, a coating material, was applied on mild steel disks by the manufacturer. The other materials are self-supporting and were obtained in sheet form for disk preparation.

Wear Bars: Wear-bar test specimens were prepared to monitor erosion-corrosion of the Type 316 stainless steel sliding guides in the venturi cone nozzle and to evaluate other alloys for use in this service. These guides are located immediately below the venturi throat where maximum gas-slurry velocities are attained. The specimens were of Type 316 stainless steel and of Haynes alloy 6B. The bars were 14 inches long by approximately 1/4-inch wide and either 1/8- or 1/4-inch thick depending on the stock available from which the bars were sheared. Each specimen was fastened to a specimen holder of Type 316 stainless steel by a clamp at each end.

Mounts and Suspensions: Spools for mounting the test specimens and also the suspension equipment for installing them in the plants were constructed mainly of Type 316 stainless steel. Bolts and nuts were annealed to remove stresses caused by cold-working in threading operations. To prevent loss of fasteners through vibration of equipment, two nuts were locked by forcing them together.

At some test locations inside plant equipment, brackets were attached as permanent fixtures by welding, and then the spools of specimens were bolted to them. In other locations, spools were fastened to existing pipe by the use of band-type clamps. In a tank, spools were suspended by means of a 1/8-inch strip or a 3-inch pipe that was bolted to the rim at the top of the tank. Sleeves (3/8-in wall by 6 in long) of soft butyl rubber were placed around the 3-inch specimen support pipe as cushions to prevent abrasion damage to the Flakeline coating or neoprene lining on a tank wall. No specimens were installed inside pipelines or fittings.

Figure 4 shows the type of spool assemblies used for mounting the corrosion test disks. Teflon insulators were used to prevent contact of dissimilar test materials.

Each wear-bar specimen was mounted by clamping both ends to a holder which was placed on one of four sliding guides at the venturi cone nozzle. The test bars were not insulated from the Type 316 stainless steel specimen holders.

Test Exposures, Conditions, and Procedures

Test specimens of materials listed in Tables I, II, and III were installed in the three scrubber systems in June 1973. Table IV gives the analysis of each of the 22 metals tested on the spools. Specimens were exposed at test locations identified by series 1000, 2000, and 3000 as shown in Figures 1, 2, and 3.

The wear-bar specimens were in the venturi system from August 29 to September 16, 1973.

Plant Operation: Early in the exposure period, all three systems were operated simultaneously, but during the latter part of the period, only the venturi and the TCA systems were operated. Information pertinent to the current exposure periods and to the accumulative operation time since the original starting date for the three systems follows.

	Current test			Operation of system since			
	Exposure period	Hours		End of first test		Original start	
		Operated	Idle	Date	Hours	Date	Hours
Venturi	6/13-9/16/73	1516	757	2/2/73	2161	9/5/72	4001
TCA	6/5-9/14/73	1861	463	2/3/73	3160	8/17/72	4827
Marble bed	6/5-8/30/73	431	1560	2/1/73	1969	8/21/72	4172

The coal used at Shawnee Power Plant contained an average of 4% sulfur (2.0 to 5.5% S) and 0.2% chlorides (trace to 0.4% Cl).

Plant Process Materials and Deposits: Typical compositions of inlet and outlet gas at the scrubber systems are tabulated below.

Component	Stack gas[a]	Scrubbed gas
SO_2, %	0.3	0.05-0.1
CO_2, %	9.8-12.3	7.4-15.0
O_2, %	6.0-6.3	4.2-8.8
H_2O, %	8	15
Fly ash, gr/std ft^3	3-5	0.02

[a] Taken from unit 10 ahead of mechanical dust collectors.

Temperature of the inlet stack gas from unit 10 boiler averaged 320°F (300°-350°F) and that of the exhaust gas after being reheated was 235° to 265°F.

Ranges in properties of liquor in the different tanks of the three scrubber systems are summarized below.

	Liquor in tanks		
	Effluent	Recycle[a]	Clarifier
Temperature, °F	75-130	85-125	70-100
Solids, % by weight			
Undissolved	7-16	7-16	0-35
Dissolved	0.7-2.0	0.8-1.4	0-2.0
pH	5.2-6.2	4.7-5.4	5.6-7.0
Ionic composition, ppm			
$SO_3^{=}$	120-600	180-220	120-600
$CO_3^{=}$	20-500	20-250	20-500
$SO_4^{=}$	900-2500	1900-2500	900-2500
Ca^{++}	2200-5500	2700-3300	2200-5500
Mg^{++}	220-550	310-400	220-550
Na^{+}	60-200	100-120	60-200
K^{+}	40-180	70-120	40-180
Cl^{-}	3000-11,000	4800-5800	3000-11,000

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[a] The values given are for recycle liquor in the TCA system; the recycle tanks in the two other systems were not used during the corrosion test period.

Table V shows analyses of deposits from the venturi and the TCA systems. The scale and solid deposits from scrubber equipment exposed to the limestone scrubbing liquors were composed mainly of the materials listed below and in the ranges of percentages shown.

Component	Percent by weight
CaO	24-26
$CaSO_3$	Trace-48
$CaSO_4$	16-72
$CaCO_3$	Trace-19
MgO	0.004-1.21
Cl	11.6[a]
Acid insoluble	0.13-60

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[a] Only one specimen.

Exposed Specimens: Photographs were made of the spools of disk-type specimens when removed from the plant as shown in Figures 5-7. Then the specimens were cleaned and their corrosion rates and physical conditions were determined as shown in Tables I through III along with properties of gas and liquor at various test points.

The wear-bar specimens are shown in Figure 8 as they appeared after the tests and before they were cleaned. Figure 9 shows new and used specimens. Results of the tests are given in the section "Venturi Scrubber--Corrosion of Test Specimens."

Inspections of Plant: Equipment in the plant systems was inspected for corrosion and erosion damage during the period September 18-20, 1973. Also, R. C. Tulis contributed information compiled from his observations and inspections throughout the test periods. Some of his observations have been included in this report.

Durometer A hardness values of rubber lining on equipment and on test specimens were measured with a Shore instrument, Type A2, ASTM 2240. Unfortunately, hardness of most lined plant equipment was not determined before plant operation; so data from the rubber vendors were ordinarily used as reference values. Temperature of the atmosphere varied from 54° to 73°F as did the temperature of equipment during the plant inspection made by the authors September 18-20, 1973. A decrease in temperature would be expected to increase rubber hardness. Values for neoprene linings for the plant equipment are summarized in Table VI. The current hardness values range from slightly lower to slightly higher than those accepted as original values (determined at 73°F, ASTM D2240-68). In general, the neoprene linings showed good resistance to deterioration.

Results of Plant Inspections and Corrosion Tests

In this section, plant inspections are described first, and then the results of corrosion tests conducted in some equipment are given. All corrosion rates were calculated on the basis of weight loss of specimens during the period of plant operation, rather than the overall exposure period.

Carbon Steel Ducts for Inlet Stack C --Plant Equipment: A product of general corrosion deposited a thin coating on the inside walls of these ducts. Small quantities of fly ash had deposited in ductwork areas where the gas flow changed directions, but this caused no apparent problem.

Stainless Steel Ducts for Inlet Flue Gas--Plant Equipment: In each duct between the carbon steel section and the scrubber inlet there are three nozzles of Type 316 stainless steel for spraying water to humidify the flue gas; some nozzles were plugged with solids. Only small deposits of solids were present in the Type 316L stainless steel ducts of the humidification sections, and only slight abrasion was noted of areas not coated with solids. However, pitting had occurred under deposits of solids during previous periods of operation.

Spray nozzles for gas humidification in these ducts were operated for the number of hours shown below.

Duct to	Spray hours	Percent of operating hours
Venturi	80	5
TCA	0	0
Marble bed	431	100

At the TCA and the marble-bed (but not the venturi) scrubbers, there are four nozzles for spraying recycle slurry to cool the inlet gas. Because of their eroded condition, the original nozzles of Carpenter 20 alloy had been replaced with new nozzles of Type 316 stainless steel; some of these were plugged with solids. Internal erosion of the nozzles was caused by high-velocity flow of cooling slurry consisting of water, limestone, and fly ash. Modification of equipment since February 1973 almost eliminated buildup of solids in this area.

The soot blower nozzle of Type 309 stainless steel in the TCA system was in good condition, but that in the marble-bed system (which was corroded severely) had been replaced with one of a different design. The new nozzle was in good condition.

Stainless Steel Ducts for Inlet Flue Gas--Corrosion of Test Specimens: Specimens located in ducts below the gas humidifier sprays corroded as follows in mils per year: less than 1 to 15 in venturi system, less than 1 to 8 in TCA system, and less than 1 to 13 in marble-bed system. (See Figs. 1, 2, and 3 for test locations 1002, 2002, and 3002; also, compare spools of specimens in Figs. 5, 6, and 7, respectively.) Tables I, II, and III list the materials tested (not identical at every test location) and their corrosion rates. Corrosion was considerably less severe in the inlet gas to the venturi (< 1 to 15 mils/yr) than it was in the previous test (1 to more than 330 mils/yr). The reason for this was that the humidification sprays were used only 5% of the time in the current tests compared with 31% previously. In the TCA inlet gas the rates were comparable in the two series of tests but not so in the marble-bed system; the reason for the difference is that the alloys that corroded severely in the first tests were omitted from the second. Several alloys, including Type 316L stainless steel, had low corrosion rates (< 1 mil/yr) in the inlet gas ducts of the three systems. This was true also in other tests which will be described later.

In the duct to the TCA system where no humidification was used, the temperature of the gas was 260° to 330°F, and the conditions of the nonmetal specimens were: Transite--good, Flakeline 200--fair, and Bondstrand--poor. All three of the materials were in poor condition in humidified gas entering the venturi and Hydro-Filter units during the previous tests, so they were not tested further in the inlet flue gas.

Venturi Scrubber--Plant Equipment: Pitting and severe erosion had occurred on the 1/4-inch-thick plates of Type 316L stainless steel mounted edgewise to support the sliding guides for the venturi cone nozzle. There are four equally spaced guide supports; two of these (north and east positions) were eroded to depths of 1-1/4 inches. Nuts and bolts in this area were worn badly and required replacement several months later. Fully annealed Type 316 stainless steel bolts have given better service in the venturi area than did Type 304 stainless steel bolts. Erosion of the venturi cone was less severe than that of the guide supports and bolts.

A test wear bar of Haynes alloy 6B mounted on the north guide support and one of Type 316 stainless steel on the east guide support had erosion-corrosion rates of 162 and 3280 mils per year, respectively, during an operation period of 380 hours (see Figs. 8 and 9). Pitting of the Haynes 6B test bar occurred only on the cold-worked (sheared) edges; the maximum depth was 27 mils. The Type 316 test bar was pitted in all areas that were not severely eroded; the maximum pit depth was 30 mils.

The neoprene-lined duct between the venturi unit and the spray tower was in good condition. Durometer A hardness of the lining was 60 (at 61°F).

Venturi Scrubber--Corrosion of Test Specimens: The specimens were installed directly below the vertically mounted venturi as shown at point 1011 of Figure 1. Gas and slurry (laden with compounds of sulfur oxides) at a high velocity caused more severe corrosion and erosion damage to specimens in this test location than in any other in the three systems. None of the specimens were destroyed completely. The erosion-corrosion rates ranged from 13 mils per year for Hastelloy C-276 to 145 for red brass. Alloys with rates of 20 to 34 mils per year listed in the order of increasing attack were: Crucible 26-1, Armco 22-13-5, Inconel 625, Type 316L, and Type 317 stainless steel. Monel 400 and red brass had rates of 122 and 145 mils per year, respectively.

The specimens of plastic-base materials Lucoflex (PVC), polyethylene, and polypropylene were in poor condition.

Figure 5 shows that spool 1011 was clean. Severe erosion of the Teflon insulators had occurred and two spacer rods on the spool had failed.

Towers in the Venturi, TCA, and Marble-Bed Systems--Plant Equipment: In general, the neoprene lining on the wall of each tower was in good condition; impingement of slurry from sprays caused slight erosion in a few small areas. Also, slight mechanical damage, possibly due to impact by foreign objects, had occurred in a few areas mainly in or near manways. The original durometer A hardness (taken from vendor's data) of the neoprene liners was 60-65. The current range of hardness values for the venturi, the TCA, and the marble bed were: 46-62, 45-65, and 66-75, respectively. All measurements were not made at the same temperature (range was 57°-72°F) because of weather changes. The hardness is expected to increase with a decrease in temperature.

Solid deposits were noted in the towers as follows (approximate thickness): venturi--0 to 1/8 inch, hard: TCA--0 to 1/2 inch, hard; and marble-bed--0 to 1/32 inch, soft.

In general, the various pieces of stainless steel hardware, such as manway deflector plates, header pipes for water and slurry, temperature probes, overflow weirs, sampling equipment, and suspension brackets were pitted in the three systems. Many spray nozzles were in good condition, some were plugged with solids, and a few were worn badly. New spray nozzles of a different design replaced the old nozzles in the marble-bed system. The Type 316L stainless steel mist eliminator in the TCA system was severely corroded, but that in the marble-bed system was affected very little.

The condition of grids in the TCA and the marble-bed towers ranged from good to poor and from clean to 50% plugged with hard solids. The greatest corrosion of grids occurred at points of contact where wires crossed; this was mainly pitting and/or crevice corrosion. Abrasion from the moving bed of wetted balls in the TCA caused failure of one grid. (Other wire grids failed after Sept. 1973 and have been replaced with rod-type grids.)

Towers in the Venturi- TCA, and Marble-Bed Systems--Corrosion of Test Specimens: Corrosion tests were not conducted in the tower of the venturi system during the previous series of tests because of plans to alter the arrangement of sprays in the tower. Consequently, the three spools (each containing 20 specimens) originally prepared for testing in that unit were exposed during the second series of tests at locations 1006, 1005, and 1004 as shown in Figure 1; the test conditions are given in Table I with the corrosion rates. Tables II and III give similar information for tests conducted in the TCA and the marble-bed towers, respectively.

Figures 5, 6, and 7 show the spools of specimens as they appeared when the tests were completed. The test medium for each spool in the three towers and the approximate amount of solids deposited on the spool are given below.

System	Spool No.	Test medium	Amount of solids on spool
Venturi	1006	Gas and liquor	Covered
	1005	Gas and liquor	Little
	1004	Gas and droplets	Partially covered
TCA	2006[a]	Gas and liquor	Thin deposit[a]
	2005	Gas and droplets	Covered
	2004	Gas and mist	None (clean)
Marble bed	3006	Gas and liquor	Thin deposit
	3005	Gas and liquor	Little

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[a] Movement of plastic spheres caused erosion on periphery of test specimens.

In the venturi tower the specimens tested at the lowest elevation (spool 1006) had the lowest corrosion rates, less than 1 to 18 mils per year; and those at the highest elevation (spool 1004) had the greatest rates, less than 1 to 42. Hastelloy C-276, Incoloy 825, and Inconel 625 had rates of about 1 mil per year at the three locations. Type 316L stainless steel had rates of less than 1, 1, and 7 mils per year at these three test locations. Pitting and crevice corrosion occurred on several alloys.

The condition of the nonmetallic materials ranged from good to poor--Bondstrand 4000, 1 good and 2 fair; Flakeline 200, 3 fair; and Transite, 1 good, 1 fair, and 1 poor.

Some of the alloys tested in the TCA and the marble-bed towers during the first series of tests were replaced in the second series by a few other alloys. Therefore, only a partial comparison of corrosion of the specimens in the three towers can be made.

Specimens at test location 2006 in the TCA tower were damaged because of abrasion on the periphery of the specimen by movement of the plastic spheres (see Fig. 6). (A wire mesh container has been installed to prevent such damage in subsequent tests.) However, a trend in resistance to corrosion in the TCA tower is evident. Alloys with corrosion rates of about 1 mil per year were Hastelloy C-276, Inconel 625, Incoloy 825, E-Brite 26-1, Crucible 26-1, Carpenter 20Cb-3, and Armco 22-13-5. Types 316L and 317 stainless steel had rates of less than 1 to 5 mils per year. The greatest attack (11 to 122 mils) was of mild steel, Cor-Ten B, Monel 400, cupro-nickel 70-30, and red brass.

The condition of nonmetallic materials was: Bondstrand 4000, 2 good; Flakeline 200, 2 fair; and Transite, 1 fair and 1 poor.

With respect to corrosion only (omitting spool 2006 because of abrasion damage), the most severe conditions in the TCA system were at the uppermost test location, 2004, in the tower near and below the chevron mist eliminator.

Only two spools of specimens were tested in the marble-bed tower. One of these was at location 3006 below the marble support grid in the liquor and inlet gas; the other was at location 3005 above the marble bed (see Fig. 3 and Table III). During the test period the system was operated only 431 hours compared with 1516 hours for the venturi and 1861 for the TCA.

At test location 3006 the corrosion rates ranged from less than 1 to 12 mils per year, and at 3005 they were less than 1 to 26 which show the conditions at the uppermost test location were more severe. Alloys that had corrosion rates of about 1 mil per year in both test locations were: Hastelloy C-276, Inconel 625, Carpenter 20Cb-3, Type 316L, and Type 317 stainless steel. Also, there were other alloys that were tested at only one of these two locations; some of these showed good corrosion resistance. Even though the period of operation was short, pitting and crevice corrosion had progressed appreciably on other alloys.

The condition of nonmetallic materials was good to poor; Bondstrand 4000, 1 good and 1 poor; Flakeline 200, 2 fair; and Transite, 2 good.

Exhaust Gas Systems--Plant Equipment: Each exhaust gas reheater for heating the scrubbed gas to between 235° and 265°F was identical (inline, oil-fired heater) in the three sytems (Figs. 1, 2, and 3) throughout the second series of corrosion tests. (Recently, an external reheater manufactured by the Bloom Engineering Co., Inc., Pittsburgh, Pennsylvania, has been installed in the venturi system.) The 3-inch-thick refractory lining in the venturi reheater had cracked badly and was being replaced with a new lining. The lining in the TCA reheater had small cracks, but it was in good condition; this unit had been relined in February 1973. An inspection was not made of the marble-bed reheater.

A stainless steel sleeve 40 inches in diameter by 4 feet tall and burner nozzles with better atomizing characteristics had been installed in each of the reheaters since February 1973. The sleeves and new nozzles improved combustion of oil before the hot combustion gases mixed with scrubber exhaust gas. Consequently, this reduced soot deposits in the stack and fan; also, oil-soot deposited in the stack was less as a result of fewer flameouts caused by quenching the flame with scrubber gas.

The Type 304 stainless steel sleeve in the venturi reheater had failed because of warpage and perforation; the sleeve in the TCA reheater was warped, but it was useable. Replacement sleeves of Type 310 stainless steel, which has better heat resisting properties than the Type 304, were being fabricated as needed; Type 310 was not available when the original sleeves of Type 304 were installed.

A heavy buildup of solids in the form of globules (some were 1 in thick by 4 in long) occurred in the stack between the reheater, and the induced-draft fan of the venturi system. The TCA stack had a dry, nonuniform deposit of solids; the maximum thickness was about 3/4 inch. A small deposit of dry solids was noted near the vacuum breaker valve of the marble-bed system.

Thickness measurements were made of the blades and the shrouds of the induced-draft fans for each system. Only slight variations (reduction of only 1 to 3 mils) were noted from the original values determined before the plants were operated. Pitting was not detected on either the moving or the stationary components of the fans. The fan for the TCA system contained the smallest volume of solids; previously, the smallest volume had been in the fan for the marble-bed system.

In the venturi system, the Type 316L stainless steel duct near the induced-draft fan cracked at the junction of the duct with the expansion bellows. One crack was 1/8-inch wide by 4 inches long. A specimen (VD-5) containing solids and liquids taken September 10, 1973, from the crack was analyzed for several compounds but not for chlorides (see Table V). However, a sample (VD-1) of solids taken earlier (Aug. 13, 1973) from the Type 316L stainless steel stack downstream of the reheater contained 11.6% chlorides. Chlorides are known to cause stress corrosion cracking of austenitic stainless steel.

Deterioration of similar equipment in the TCA and the marble-bed systems has not been noted. However, efforts will be made to detect hairline cracking (if present) during future inspections of the stainless steel equipment, especially in the areas of welds.

Exhaust Gas Systems--Corrosion of Test Specimens: Corrosion test specimens were mounted in the exhaust stacks in each system 8 to 10 feet downstream from the reheater as shown at points 1007, 2007, and 3007 (Figs. 1, 2, and 3). Temperature of heated exhaust gas in contact with the specimens was usually between 235° to 265°F. Tables I, II, and III give corrosion data. Figures 5 through 6 show the soot- and ash-covered specimens after exposure. The greatest deposit of solids occurred on the spool (3007) in the venturi system.

The corrosion rates of test specimens in the heated exhaust gas were: in the TCA stack, 1 to 2 mils per year; in the venturi, 1 to 16; and in the marble-bed, 1 to 18. Alloys that had rates of about 1 mil per year in each of the three systems were: E-Brite 26-1, Hastelloy C-276, Inconel 625, and Type 317 stainless steel. Several other alloys had low rates in the TCA and marble-bed systems. The range of rates for mild steel and for Type 316L stainless steel in the three exhaust gas systems were 2-18 and 1-3, respectively. Pitting depth in mils ranged from minute to 13 for specimens in the three exhaust gas systems.

The condition of the nonmetallic materials was: Bondstrand 4000, 1 poor; Flakeline 200, 2 poor; and Transite, 3 good. In some cases, tests of materials that failed in the first series of tests were not repeated.

The condition of the Teflon insulator and spacers on spool 3007 (marble-bed system) indicates that the stack had been heated well above the normal operating temperature at least for a short time during the test period.

Effluent Hold Tanks--Plant Equipment: An effluent hold tank 20 feet in diameter and 21 feet tall is located directly under each scrubber tower: D-101 for the venturi, D-201 for the TCA, and D-301 for the marble-bed systems. The shells are made of A-283 carbon steel coated inside (80 mils minimum thickness) with Flakeline 103 manufactured by the Ceilcote Company. This coating is a Bisphenol-A type of polyester resin filled with flake glass (25-35%).

Each tank was in good condition except for minute cracks at the junction of some baffles with the tank walls and for damage due to abrasion of small areas in the TCA tank. The 15-foot-long specimen suspension pipe was not anchored securely, and this allowed the turbulent slurry to move the pipe enough to cause the butyl sleeves (cushions) to abrade through the top coat of the Flakeline. Damage to another small area of the lining was done by similar motion of a temporary downcomer of bare 4-inch carbon steel pipe which was installed after February 1973.

Stains of iron rust indicated that the cracks penetrated the Flakeline coating. Rust stains were noted on the wall above the immersion line; apparently these stains were carried by fluids dripping from mild steel equipment located above. Scale about 1/32-inch thick was flaking off the walls.

In general, the downcomers of Bondstrand (8-in diameter) showed no evidence of attack, but those of Type 316L stainless steel (4-ft diameter) were pitted. The neoprene-covered agitator blades showed some wear on leading edges and in some cases, slight impact damage was noted; apparently this was caused by sharp foreign objects. The hardness of the neoprene had changed little if any (see Table VI). The covering on the agitator shafts was in good condition.

Effluent Hold Tanks--Corrosion of Test Specimens: Corrosion test specimens were mounted in the effluent hold tanks 15 feet below the top. Figures 1 through 3 identify the locations and Figures 5 through 7 show photographs of test specimens by numbers--1008 for the venturi, 2008 for the TCA, and 3008 for the marble-bed systems. Tables I through III show that corrosion was less than 1 mil per year for 12 alloys in the venturi tank, 16 in the TCA, and 8 in the Marble-bed tank; Type 316L stainless steel was one of these in each tank.

The rates in mils per year for Cor-Ten B and mild steel in the effluent hold tanks were 7 and 10 in the venturi, less than 1 for both alloys in the TCA, and 79 and 99 in the marble bed, respectively. Red brass, cupro-nickel 70-30, and Hastelloy B had rates of 21, 26, and 13 mils in the marble-bed tank; these alloys were not attacked appreciably in the venturi and the TCA tanks. The temperature and the pH of slurries in the three tanks were comparable. However, their ionic composition as tabulated below shows that the marble-bed effluent slurry had an appreciable higher content of $CO_3^{=}$, Ca^{++}, Na^{+}, and Cl^{-} than the effluent slurry of the two other systems.

To evaluate the effect of any and all of these components in the slurry on corrosion of materials of construction, a daily analysis, such as the one on the following page, would be necessary. Not only is the range in composition important, but also the composition with respect to time (weighted analysis) is of importance, especially if there are areas of composition that are critical with respect to corrosion.

Ionic Composition of Effluent Slurry in System, ppm

Ion	Venturi	TCA	Marble bed
$SO_3^{=}$	120-600	180-220	150-250
$CO_3^{=}$	25-70	20-250	180-500
$SO_4^{=}$	900-2500	1900-2500	1800-2000
Ca^{++}	2200-5100	2700-3300	4200-5500
Mg^{++}	220-510	310-400	450-550
Na^{+}	60-140	100-120	130-200
K^{+}	40-180	70-120	90-160
Cl^{-}	3000-10,000	4800-5800	9000-11,000

The condition of the nonmetallic materials tested in the effluent hold tanks for the three systems was: Bondstrand 4000, 3 good; Flakeline 200, 3 fair; and Transite, 3 good.

In comparing the results of the first series of corrosion tests in the effluent liquor with the results from the second series, the maximum rates for metals were higher in the venturi and the TCA systems and much lower in the marble bed in the first series than in the second. Pitting and crevice corrosion were common in both. The condition of the nonmetallic materials tested was about the same for both series of tests.

Recirculation Tanks--Plant Equipment: Each of the scrubbing systems has a recirculation tank 5 feet in diameter by 21 feet tall. These are designated as D-104 for the venturi, D-204 for the TCA, and D-304 for the marble-bed systems. These tanks were lined with neoprene sheet 1/4-inch thick, and the blades and shaft of their agitators were also covered with neoprene.

The recirculation tank for the venturi system and that for the marble-bed system were not used during the second series of corrosion tests. However, this equipment was used during the interval between the first and the second series of tests. The linings on all of the tank walls and the agitators were in good condition. A thin scale had deposited that would protect the surface. Durometer A hardness values for the neoprene linings were fairly consistent (see Table VI), although they were higher than the original hardness values. The coating on the agitator blades in the TCA tank (D-204) had lower hardness values than those in tanks D-104 and D-304 (53 to 56 vs.66 to 73).

The wire cage over the slurry outlet line in the TCA tank was plugged with solids so it was removed later.

Recirculation Tanks--Corrosion of Test Specimens: Corrosion test specimens were not installed in recirculation tank D-104 (venturi) in the second series of tests. Specimens were suspended 15 feet below the top in tank D-204 (TCA) and 8 feet below the top in tank D-304 (marble bed). However, tank D-304 was not used during the test period and the exposure of specimens in that tank was nothing more than a plant atmospheric test (test location 3012, see Fig. 3 and Table III).

All alloys exposed in the atmospheric test in recirculation tank D-304 had corrosion rates of less than 1 mil per year except for Cor-Ten B and mild steel which had rates of 11 and 12, respectively. The nonmetallic materials Bondstrand 4000, Flakeline 200, and Transite were in good condition.

Corrosion rates were low for specimens in recirculation tank D-204; mild steel had a rate of 1 mil per year and rates for the other alloys were less than 1. Crevice corrosion and pitting occurred on some materials. The condition of nonmetallic materials Bondstrand 4000 and Transite was good, but because of erosion damage, Flakeline 200 was only fair.

Clarifier Tanks--Plant Equipment: Clarifier tanks D-102 for the venturi and D-302 for the marble-bed systems are 20 feet in diameter and 15 feet tall; and tank D-202 for the TCA system is 30 feet in diameter and 15 feet tall. Each tank has a cone-shaped bottom that is positioned 3 to 5 feet above the foundation elevation. The tanks are of A-283 carbon steel coated inside with Flakeline 103. Mechanical equipment inside the clarifiers is made of Type 316L stainless steel. Tank D-101 had not been drained, and therefore was not inspected.

Small defects common to both D-202 and D-302 tanks were cracks in the Flakeline 103 coating evidenced by rust bleeding through at the junction of the tank wall with the cone bottom and under the launder. This condition was noted at the end of the first test (Feb. 1973).

In the TCA tank (D-202) a scratch through the top coat of Flakeline 103 had been cut on the inside periphery 1 foot above the bottom by the stainless steel plow. The tip of the plow has since been trimmed to prevent further damage. In the marble-bed tank (D-302) rust spots were found at levels of 3 and 6 feet above the bottom on the northwest wall. The stainless equipment in both tanks showed no evidence of attack.

Clarifier Tank--Corrosion of Test Specimens: A spool of corrosion test specimens was suspended in the slurry 5 feet below the launder in clarifier tanks D-102, D-202, and D-302. These tanks are not shown in Figures 1 through 3. Items 1013, 2013, and 3013 in Figures 5, 6, and 7 are photographs of specimens after exposure. Tables I through III give corrosion data.

The corrosion rates were less than 1 mil per year for most alloys tested in the three clarifier tanks. The highest rates were for mild steel and Cor-Ten B; these were, in mils per year, 1 and 2 in the venturi; 2 and 2 in the TCA, and 6 and 7 in the marble bed, respectively. The higher rates in the marble-bed clarifier tank were probably caused by the long period of idle time (1560 hr idle vs. 431 hr of operation). /In another test (3012, see Table III) conducted in atmospheric conditions throughout the exposure period, the corrosion rates were 12 and 11 mils per year for mild steel and Cor-Ten B./ These results show that corrosion of the two alloys was greater under atmospheric conditions than it was in either the recirculation tank or the clarifier tank. Pitting and crevice corrosion had progressed more on specimens in the venturi clarifier than on those in the TCA and marble-bed clarifier tanks.

The condition of the nonmetallic materials was: Bondstrand 4000, 1 good and 1 fair; Flakeline 200, 3 fair; Transite, 3 good; and polypropylene, 1 good.

Clarified Process Water Hold Tanks--Plant Equipment: Clarified water hold tanks D-103 for the venturi and D-303 for the marble-bed systems are 10 feet in diameter and 9 feet tall. Tank D-203 for the TCA system is 13 feet in diameter and 9 feet tall. Each tank has four vertical baffles welded to a shell of carbon steel and lined with 1/4 inch of neoprene of durometer A hardness of 55-60. Each tank has a three-blade agitator with diameter as follows: 14 inches in D-103 and D-303 and about 42 inches in D-203. The agitators and shafts were covered with neoprene.

In general the neoprene tank linings were in good condition; the partial separation of a lap joint (8-in section) in the TCA tank as noted in the previous report had not progressed further. The covering on the agitator shaft and blade assembly was in good condition except for moderate wear on the leading edge of the blades and minor impact damage on some blades. These exceptions were also reported previously.

The durometer A hardness of the linings (see Table VI) are consistent for the three tanks and agitator assemblies, but these values are higher than the original hardness values. However, the temperature of the liners was 18°F lower than that specified (73°F) in the standard for testing the hardness of rubber, ASTM designation D2240-68.

Reslurry Tank--Plant Equipment: Tank D-401 is used for reslurrying waste solids removed in the clarifier. It is identical in size and construction to storage tank D-103 already described. The tank was half full of water when inspected. The neoprene lining above the liquid line was in good condition and its durometer A hardness was 65 to 71 (at 55°F).

Neoprene-Lined Centrifugal Pumps--Plant Equipment: During the first series of corrosion tests in the scrubbing systems, Hydroseal pumps were in service; their impeller diameters were 12, 17, or 20 inches. The centrifugal pumps were manufactured by the Allen-Sherman-Hoff Company. All wetted parts were lined with neoprene. In February 1973 some of the Hydroseal pumps were converted to Centriseal, which has air instead of water for a seal. Seal water required by the Hydroseal pumps added more water to the system than could be tolerated in closed-loop operation. Conversion of Hydroseal pumps to Centriseal pumps requires replacement of (1) the shell half-suction side, (2) the shell half-engine side, (3) the impeller, and (4) the stuffing box. In addition, an adjusting plate must be added, the lantern ring has to be moved to a new position, and the pump has to be repacked.

The pumps that were converted from Hydroseal to Centriseal are listed below.

Scrubber system	Pumps converted from Hydroseal to Centriseal
Venturi	G-101, G-103, G-104
TCA	G-201, G-203, G-204
Marble bed	G-301, G-303A, G-304

Only pumps in the TCA system were inspected (Sept. 18-20, 1973). The pumps inspected that had not been converted were G-202 and G-206. Those inspected that had been converted to Centriseal were G-201, G-203, and G-204. The durometer A hardness of the neoprene linings ranged from 59 to 68 except for pump G-206 where it was 51 to 55.

The damage observed in the Hydroseal and in the Centriseal pumps was common to both. However, greater sleeve wear resulted when using Centriseal because solids were completely washed back into the pumps; thus sleeves on several pump shafts had been worn by the packing. The neoprene liners of several pumps had been damaged by some hard object that caused grooving, impact damage, and/or wear.

Piping--Plant Equipment: Neoprene-lined piping was inspected at the inlet and the outlet of the pumps that were dismantled. All visible areas of the linings were in good condition. The hardness values of the neoprene linings were not determined.

Valves--Plant Equipment: The stainless steel check valve at the discharge of pump G-201 was inspected. The body of the valve is of cast stainless steel ASTM A-351, Grade CF-8M. The plate (hinged vertically at the center of the cavity) is of Type 316 stainless steel, and it seats on a neoprene ring. The valve was in good condition; the surface of the plate was smooth and polished.

Discussion

Process Materials: In the SO_2 removal plant, the inlet gas, the limestone absorbent, and their reaction products are corrosive and/or abrasive. Components of gas, such as CO_2, O_2, and SO_2, dissolve sparingly to make the condensate or water corrosive. Fly ash in stack gas and the limestone in absorbent slurry are abrasive, especially in high-velocity streams. Slurry containing limestone, sulfite, sulfate, fly ash, and chlorides forms deposits on metal to cause localized corrosion.

Materials of Construction: Materials in the plant consist mainly of: (1) carbon steel in the inlet duct for stack gas from the power plant; (2) Type 316L stainless steel in the scrubbing system ducts, the venturi scrubber, the removable internal parts of scrubber towers, the outlet gas duct, the fans, and the stack: (3) neoprene-lined carbon steel in the venturi afterspray and the TCA and marble-bed towers; (4) neoprene-lined carbon steel in the recirculation, clarified process water, and reslurry tanks; (5) Bondstrand and Type 316L stainless steel downcomers to the effluent hold tanks; (6) Flakeline 103-lined carbon steel in the effluent hold and clarifier tanks; (7) refractory-lined gas reheater, and (8) neoprene-lined pumps and piping.

Corrosion--Plant Equipment: In general, materials used in construction of the three scrubbing systems showed good resistance to attack. Carbon steel ducts were corroded slightly by inlet stack gas when at temperatures below the dew point.

Inlet stack gas, after being humidified with spray water, attacked stainless steel ducts and nozzles as follows: slight erosion of bare duct surfaces; concentration cell-type corrosion (pitting and crevice) of surfaces underlying deposits; and severe corrosion and erosion of surfaces (nozzles or projections) subjected to impingement.

In the venturi scrubber, the limestone slurry and gas discharging at high velocity corroded and eroded stainless steel parts, but apparently did not damage neoprene lining in the duct.

In the towers of the three systems, pitting and crevice corrosion were common types of attack of stainless steel removable parts; this occurred in stagnant areas (under deposits of solids). Movement of the mobile packing (hollow plastic spheres) caused erosion failure of grid wire in the TCA absorber.

Severe corrosion occurred on the top surface of a chevron-type mist eliminator of Type 316L stainless steel in the TCA tower. It is likely that mist passing through a wash tray located below collected on the chevron mist eliminator and evaporated to form a residue high in compounds of chlorine and sulfur which are corrosive. Pits observed in the outlet duct from the venturi afterscrubber might also have been caused by such a residue of chlorine and sulfur compounds. Frequent washing to remove residue might decrease the corrosion.

The demister in the marble-bed tower was clean and was not pitted.

A polypropylene four-pass vane-type mist eliminator purchased from Chemico was used in the venturi tower for about 40 days of operation. During this period the unit showed no evidence of chemical attack, but the top side was damaged severely by impact of heavy solids that fell from the duct above. Also some damage was caused by rough handling of the unit. Perhaps further testing of plastic mist eliminators is justified. Subsequently, the plastic unit was replaced by one of stainless steel.

Nozzles of stainless steel were fairly durable for spraying limestone slurry in the towers, although replacement nozzles will be required occasionally.

Rubber lining in the tower shells, though coated usually with slurry solids, was generally in good condition.

Exhaust gas stacks of Type 316L stainless steel exposed to gas reheated to between 235° and 265°F were not attacked by general corrosion. However, cracking occurred near an expansion joint downstream from the I.D. fan in the venturi system. Stress corrosion might have caused this damage.

Sleeves and improved burner nozzles installed at the gas reheaters did improve fuel oil combustion and thereby minimize troublesome soot deposition and a potential fire hazard in exhaust gas stacks.

Flakeline 103 linings in the effluent hold tanks and clarifier tanks were generally in good condition except for cracks near attachments (such as baffles and weirs) to the walls and for abrasive damage caused by auxiliary equipment that had been improperly anchored or adjusted.

Bondstrand downcomers to the effluent hold tanks were in good condition; downcomers of Type 316L stainless steel were pitted.

Neoprene linings were in good condition in the recirculation, clarified water, and reslurry tanks. Slight to noticeable wear was apparent on neoprene-covered agitators, and impingement damage caused by hard, foreign objects had occurred to the covering of a few agitator blades. Neoprene-lined piping was inspected near pumps and it appeared to be in good condition. The condition of linings of casings and coverings on impellers in centrifugal pumps of the TCA system ranged from good to poor. (Pumps in other systems were not inspected by the authors.)

Corrosion--Test Specimens: Because identical spools if disk-type specimens were tested in the first series of corrosion tests, a realistic comparison could be made of their corrosion resistance at each test location in the three scrubber systems. However, in the second series of tests the spools were not identical. Several materials that showed poor resistance to corrosion at some locations in the previous tests were omitted or replaced with a few other materials at these test locations. The alloys added were Armco 22-13-5, red brass, Crucible 26-1, and Types 201 and 317 stainless steel. The nonmetallic materials added were Lucoflex (PVC), polyethylene Type III, and polypropylene.

Although a clear-cut comparison of corrosion resistance offered by these materials cannot be made, the following tabulation lists the number of alloys with corrosion rates (on the basis of weight loss only) within a few arbitrary ranges for each scrubber system. The tabulation does not include results from specimens that were eroded severely at test locations 1011 and 2006. Those results are shown in Table VI.

Range of corrosion rates	Number of alloys tested in Venturi	TCA	Marble bed
< 1-7	9	15	14
< 1-21	7	4	3
< 1-71	5	1	0
< 1-122	0	1	1
1-21	1	1	2
5-99	0	0	2

In general, corrosion was least severe in the TCA system (15 alloys in the lowest range) and most severe in the venturi system (only 9 alloys in the lowest range). This was also the trend in the first series of tests. The nine alloys with corrosion rates of less than 1 to 7 mils per year in the three systems were: Armco 22-13-5, Carpenter 20Cb-3, Crucible 26-1, E-Brite 26-1, Hastelloy C-276, Incoloy 825, Inconel 625, Type 316L, and Type 317 stainless steel.

Tables I, II, and III list the corrosion rate for each alloy and identify localized attack, when it occurred, in each scrubber system.

Table VII is a compilation of data for all materials tested in the three systems without identifying the test conditions. This table summarizes information on pitting, crevice corrosion, and other types of attack in addition to corrosion on the basis of weight loss. Alloys that showed good resistance both to pitting and crevice corrosion were Armco 22-13-5, red brass, cupro-nickel 70-30, and Hastelloy C-276. Alloys Hastelloy B and Inconel 625 each had only one minute pit. The 16 other alloys were definitely susceptible to localized attack.

Because the copper-bearing alloys cupro-nickel 70-30 and Monel 400 showed resistance to pitting and crevice corrosion in the first series of tests, red brass, which costs less, was included in the second series of tests. The corrosion rates for red brass were 1 to 21 mils per year (only 10 specimens tested) with no pitting or crevice corrosion. However, the weld was attacked enough to indicate that perhaps a different filler metal and/or a modified welding procedure might improve the corrosion resistance of red brass.

The corrosion rate of Type 201 stainless steel was about the same as that of Type 304L; both alloys are highly susceptible to localized corrosion in the scrubber systems.

When Type 317 stainless steel was tested, it was expected that the greater molybdenum content of this alloy as compared with that of Type 316 (3-4% vs. 2-3%, respectively) would reduce the frequency of pitting and crevice corrosion compared with that of Type 316L stainless steel. However, the current tests show no definite improvement on the basis of 8 and 23 specimens tested of alloy Types 317 and 316L, respectively.

Each of the 22 alloys tested showed good resistance at one or more test locations in each scrubber system. Table VIII gives the approximate comparative cost of most of the alloys based on the cost of common Type 304 stainless steel as unity (1.00).

The condition of the nonmetallic materials tested with respect to the number of specimens in good, fair, and poor condition were: Bondstrand 4000, 10, 3, and 3; Flakeline 200, 1, 15, and 2; and Transite, 15, 2, and 2. Only one specimen each of Lucoflex (PVC) and polyethylene were tested; both specimens were poor. The three specimens of polypropylene were two good and one poor.

This corrosion study is being continued on materials of construction for the SO_2 removal test facility at Shawnee Power Plant.

Summary

Test specimens exposed for about 3 months in three test SO_2 removal systems at Shawnee Power Plant were evaluated for corrosion and wear.

The most severe damage occurred in plant areas exposed to humidified stack gas containing fly ash, CO_2, O_2, and SO_2 at elevated temperature and high velocity; to gas and slurry discharging at high velocity from the venturi; and to gas and mist leaving an absorber.

Metals covered by limestone-fly ash deposits were not eroded but were subject to corrosion of the concentration cell type.

Twenty-two alloys were tested either at all or at some of the twenty-three exposure areas in the three scrubber systems. The maximum corrosion rate in mils per year for the five most durable alloys exposed at all the test locations were: Hastelloy C-276, less than 1; Inconel 625, 1; Incoloy 825, 2; Carpenter 20Cb-3, 2; and Type 316L, 7.

Nine specimens tested of Armco 22-13-5 and 8 of Type 317 stainless steel gave rates of 1 mil per year or less; alloy 22-13-5 showed good resistance to pitting and crevice corrosion, but Type 317 was affected by both types of attack.

Of the alloys that showed great resistance to corrosion, Hastelloy C-276 is the most durable and the most expensive. Type 316L stainless steel ranks fifth in durability and about twelfth in cost (considering all alloys tested). Comparative evaluations are difficult to make for the second series of tests because all spools of test specimens were not identical.

Neoprene-lined towers, ducts, and tanks were durable. Some wear was apparent on neoprene linings of pumps and agitators.

Plastics, such as polyester and epoxy, were less durable than rubber as lining materials.

In general, less corrosion was observed in the second series of tests than in the first series; no specimens were completely destroyed in the second series.

This corrosion study is being continued on materials of construction for the SO_2 removal test facility at Shawnee Power Plant.

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TABLE I

Corrosion Tests Conducted in the Venturi System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--June 15 to Sept. 16, 1975; operating time--1516 hours or 63.2 days; and idle time--757 hours or 31.5 days)

Corrosion specimens Exposed in . . . . Locations (see Fig. 1), Reference No.	Inlet gas 1002	Gas and spray 1011	Gas and liquor 1006	Gas and liquor 1005	Gas and droplets 1004	Exhaust gas (heated) 1007	Effluent liquor 1008	Liquor in clarifier 1013
Gas								
Temperature, °F	275-350[a]	80-170	80-160	80-150	80-140	235-265	-	-
Velocity, ft/sec	40-60	30-50	5-7.5	5-7.5	5-7.5	40-60	-	-
Flow rate, 1000's acfm at 350°F	20-30	15-25	15-25	15-25	15-25	20-30	-	-
Composition, % by volume								
SO_2	0.3	0.2	0.2	0.2	0.2	0.1	-	-
CO_2	12.5	12.0	12.0	12.0	12.0	11.7	-	-
O_2	6.5	6.5	6.5	6.5	6.5	6.5	-	-
H_2O	8	15	15	15	15	15	-	-
Fly ash, gr/std ft³	3-5	0.02	0.02	0.02	0.02	0.02	-	-
Liquor								
Temperature, °F	-	-	-	-	-	-	90-130	70-100
Solids, undissolved, % by wt	-	-	-	-	-	-	8-16	0-35
Solids, dissolved, % by wt . . .	-	-	-	-	-	-	0.7-1.9	0-2.0
pH	-	-	-	-	-	-	5.5-6.2	5.8-7.0
Ionic composition, ppm								
$SO_3^{=}$	-	-	-	-	-	-	120-600	120-600
$CO_3^{=}$	-	-	-	-	-	-	25-70	25-70
$SO_4^{=}$	-	-	-	-	-	-	900-2500	900-2500
Ca^{++}	-	-	-	-	-	-	2200-5100	2200-5100
Mg^{++}	-	-	-	-	-	-	220-510	220-510
Na^{+}	-	-	-	-	-	-	60-140	60-140
K^{+}	-	-	-	-	-	-	40-180	40-180
Cl^{-}	-	-	-	-	-	-	5000-10,000	5000-10,000
Corrosion rate of metals[b], mils/yr								
Aluminum 5005, weld ER1100 . . .	-	-	1[c]	16	42, P84	-	-	1[c], P9
Armco 22-13-5, weld Armco 22-13-5	< 1	26[d]	-	-	-	-	< 1	-
Brass, red, weld Ozweld 250 . .	7	145[d]	-	-	-	16	-	-
Carpenter 20Cb-3, weld Carpenter 20Cb-3	< 1	64[d]	< 1	< 1[c], P18	2[c], P17	2, P3	< 1	< 1
Cor-Ten B, weld E8018-C3	-	-	18[d]	50	51	8	7	2[c], Pm
Crucible 26-1, weld E-Brite 26-1	< 1	20[c,d]	-	-	-	-	-	-
Cupro Nickel 70-30, weld B259 RCuNi	3	71	1	6	32[e]	5[e]	1	1
E-Brite 26-1, weld E-Brite 26-1	-	-	1, P14	2[c], P24	1[c], P17	1, P3	< 1	< 1
Hastelloy B, weld Hastelloy B	4	90[d]	1	8	11	2	1	1, Pm
Hastelloy C-276, weld Hastelloy C-276	< 1	13[d]	< 1	< 1	< 1	< 1	< 1	< 1
Incoloy 800, weld Inconel 82 . .	1[f], P9	-	< 1[c], P3	1[c], P19	21[c], P10	2, P1	< 1, P14	< 1
Incoloy 825, weld Incoloy 65 . .	< 1	55[d]	< 1	< 1[c]	1[c]	2	< 1	< 1
Inconel 625, weld Inconel 625 .	< 1	28[d]	< 1	< 1	< 1	< 1	< 1	< 1
Mild steel, A-285, weld E6012 .	-	-	16[d]	57	60	11, P7	10[c]	1[c], Pm
Monel 400, weld Monel 60	2	122[d]	2	10	55[e,g]	16	1	2[c]
Type 201, weld Type 316	15[f], P16	141[d]	-	-	-	5, Pm	< 1[c], P11	< 1
Type 304L, weld Type 308L . . .	15, P20[g]	-	1[c], P10	2[c], P16	17, P15	5	< 1[c], P12	< 1
Type 316L, weld Type 316L . . .	< 1	32[c,d]	1	< 1[c], P11	7[c], P10	5, Pm	< 1	< 1
Type 317, weld Type 317	< 1	36[c,d]	-	-	-	1, P8	-	-
Type 410, weld Type 309	-	-	< 1[c], P7	3[c], P9	21[c], P20	4	-	2[c], Pm
Type 446, weld Type 309	-	-	1[c], P7	5[c], P15	17[c], P30	5, P12	< 1[c], P4	< 1[c], P4
USS 18-18-2, weld Inconel 82 . .	-	-	< 1[c], P10	5[c], P13	18[c], P15	2	< 1[c], P24	< 1[c], P25
Evaluation of nonmetallic materials[h]								
Bondstrand 4000 (Fiber glass-reinforced epoxy)	-	-	Fair	Fair	Good	-	Good	Fair
Flakeline 200 (inert flakes and polyester resin).	-	-	Fair	Fair	Fair	-	Fair	Fair
Duroflex, polyvinyl chloride . .	-	Poor	-	-	-	-	-	-
Polyethylene Type III (high density)	-	Poor	-	-	-	-	-	-
Polypropylene	-	Poor	-	-	-	-	-	-
Ceramic								
Transite (Portland cement and asbestos)	-	-	Fair	Good	Poor	Good	Good	Good

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[a] During the test period, the humidification sprays were used 80 hours (5% of operating time); the gas temperature was about 125°F while spray water was used.

[b] "P" preceding a number indicates pitting during the exposure period to the depth in mils shown by the number, and "Pm" indicates minute pits.

[c] Crevice corrosion at Teflon insulator.

[d] Erosion and corrosion.

[e] Dealuminification.

[f] Localized attack of parent metal.

[g] Attack of weld.

[h] Evaluation: good, little or no change in condition of specimen; fair, definite change—probably could be used; poor, failed or severely damaged.

TABLE II

Corrosion Tests Conducted in the TCA System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--June 5 to Sept. 14, 1973; operating time--1861 hours or 77.5 days; and idle time--463 hours or 19.5 days)

Corrosion specimens Exposed in Locations (see Fig. 2), Reference No.	Inlet gas 2002	Gas and liquor 2006	Gas and droplets 2005	Gas and mist 2004	Exhaust gas (heated) 2007	Effluent liquor 2008	Recycle liquor 2012	Liquor in clarifier 2015
Gas								
Temperature, °F	260-310	70-125	70-120	70-120	235-265	-	-	-
Velocity, ft/sec	35-50	8-9	7-8	6-7	35-50	-	-	-
Flow rate, 1000's acfm at 300°F	20-25	15-16	15-16	15-16	20-25	-	-	-
Composition, % by volume								
SO_2	0.3	0.05	0.05	0.05	0.05	-	-	-
CO_2	9.8	7.4	7.4	7.4	7.4	-	-	-
O_2	6.5	8.8	8.8	8.8	8.8	-	-	-
H_2O	8	15	15	15	15	-	-	-
Fly ash, gr/std ft^3	3-5	0.02	0.02	0.02	0.02	-	-	-
Liquor								
Temperature, °F	-	-	-	-	-	110-125	85-125	85-100
Solids, undissolved, % by wt	-	-	-	-	-	7-16	7-16	0-35
Solids, dissolved, % by wt	-	-	-	-	-	0.8-1.4	0.8-1.4	0.8-1.4
pH	-	-	-	-	-	5.2-5.8	4.7-5.4	5.6-7.0
Ionic composition, ppm								
$SO_3^{=}$	-	-	-	-	-	180-220	180-220	180-220
$CO_3^{=}$	-	-	-	-	-	20-250	20-250	20-250
$SO_4^{=}$	-	-	-	-	-	1900-2500	1900-2500	1900-2500
Ca^{++}	-	-	-	-	-	2700-3300	2700-3300	2700-3300
Mg^{++}	-	-	-	-	-	310-400	310-400	310-400
Na^{+}	-	-	-	-	-	100-120	100-120	100-120
K^{+}	-	-	-	-	-	70-120	70-120	70-120
Cl^{-}	-	-	-	-	-	4800-5800	4800-5800	4800-5800
Corrosion rate of metals,[a] mils/yr								
Aluminum 3003, weld ER1100.	< 1	60[b,c]	8	-	1, P13	1[d]	< 1, P3	< 1,[b] P3
Armco 22-13-5 weld Armco 22-13-5	-	-	< 1	< 1	-	-	-	< 1
Brass, red, weld Oxweld 25M	-	4[c]	-	11[d]	2	-	-	-
Carpenter 20Cb-3 weld Carpenter 20Cb-3	< 1	1[c]	< 1	< 1	< 1	< 1	< 1	< 1
Cor-Ten B, weld E8018-C3	8	71[b,c]	21	-	1, P3	< 1	< 1	2[e]
Crucible 26-1 weld E-Brite 26-1	-	1,[b] P14	< 1,[b] P12	< 1	-	-	-	-
Cupro Nickel 70-30 weld B259 RCuNi	1	5[c]	6	49	2	< 1	< 1	< 1
E-Brite 26-1 weld E-Brite 26-1	< 1	1[b,c]	< 1,[b] P8	Pm, -[b]	< 1,[b] P2	< 1	< 1, Pm	< 1
Hastelloy B weld Hastelloy B	< 1	12[c]	5	13	< 1	< 1	< 1	< 1
Hastelloy C-276 weld Hastelloy C-276	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Incoloy 800, weld Inconel 82	< 1	-	2,[b] P22	1,[b] P14	< 1,[b] Pm	< 1	< 1,[b] Pm	< 1
Incoloy 825, weld Incoloy 65	< 1	1[b,c]	< 1	< 1[b]	< 1,[b] P7	< 1	< 1	< 1
Inconel 625, weld Inconel 625	< 1	1[c]	< 1	< 1	< 1	< 1	< 1	< 1
Mild steel, A-283, weld E6012	7	68[b,c]	19	122	2, P9	< 1, Pm	1	2, Pm
Monel 400, Monel 60	< 1	31[c,d]	21[d]	19[d]	1	< 1	< 1	1[d]
Type 201, weld Type 316	-	4,[b,c] P7	-	2,[b] P29	-	-	< 1,[b] Pm	-
Type 304L, weld Type 308L	< 1	3,[b,c] P17	-	2,[b] P12	< 1, P7	< 1,[b] P4	< 1,[b] P1	< 1[b]
Type 316L, weld Type 316L	< 1	2,[b,c] P2	< 1	5[b]	< 1,[b] P10	< 1	< 1	< 1
Type 317, weld Type 317	-	1[b,c]	-	< 1	-	-	-	-
Type 410, weld Type 309	< 1	6,[b,c] P5	2, P20	-	-	< 1,[b] Pm	-	-
Type 446, weld Type 309	< 1	-	-	-	< 1,[b] P9	< 1,[b] Pm	< 1,[b] Pm	< 1, Pm
USS 18-18-2, weld Inconel 82	< 1	5,[b,c] P6	1,[b] P15	-	< 1,[b] Pm	< 1[b]	< 1,[b] Pm	< 1, Pm
Evaluation of nonmetallic materials								
Bondstrand 4000 (Fiber glass-reinforced epoxy)	Poor	-	Good	Good	Poor	Good	Good	Good
Flakeline 200 (inert flakes and polyester resin)	Fair	-	Fair	Fair	Poor	Fair	Fair	Fair
Polypropylene	-	-	-	Good	-	-	-	-
Ceramic								
Transite (Portland cement and asbestos)	Good	Poor	Fair	-	Good	Good	Good	Good

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[a] "P" preceding a number indicates pitting during the exposure period to the depth in mils shown by the number, and "Pm" indicates minute pits.

[b] Crevice corrosion at Teflon insulator.

[c] Specimen worn by movement of plastic balls.

[d] Attack of weld.

[e] Attack of heat-affected zone of weld.

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TABLE III

Corrosion Tests Conducted in the Marble Bed System of the Limestone - Wet-Scrubbing Process for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period--June 8 to Aug. 30, 1975; operating time--431 hours or 18 days;
and idle time--1560 hours or 65 days)

Corrosion specimens Exposed in Locations (see Fig. 3).	Inlet gas	Liquor and inlet gas	Gas and liquor	Exhaust gas (heated)	Effluent liquor	Recycle liquor	Liquor in clarifier
Reference No.	3002	3006	3005	3007	3008	3012[a]	3013
Gas							
Temperature, °F	120-150	95-135	95-130	235-265	-	-	-
Velocity, ft/sec	30-42	5-7	5-7	35-65	-	-	-
Flow rate, 1000's acfm at 330°F	15-21	15-21	15-21	17-33	-	-	-
Composition, % by volume							
SO_2	0.3	0.1	0.1	0.1	-	-	-
CO_2	16.0	15.0	15.0	15.0	-	-	-
O_2	6.0	4.2	4.2	4.2	-	-	-
H_2O	15	15	15	15	-	-	-
Fly ash, gr/std ft^3	3-5	0.02	0.02	0.02	-	-	-
Liquor							
Temperature, °F	-	-	-	-	75-125	-	75-100
Solids, undissolved, % by wt	-	-	-	-	9-11	-	0-20
Solids, dissolved, % by wt	-	-	-	-	1.5-2.0	-	0-2.0
pH	-	-	-	-	5.5-5.8	-	6.0-6.8
Ionic composition, ppm							
$SO_3^{=}$	-	-	-	-	150-250	-	150-250
$CO_3^{=}$	-	-	-	-	180-500	-	180-500
$SO_4^{=}$	-	-	-	-	1800-2000	-	1800-2000
Ca^{++}	-	-	-	-	4200-5500	-	4200-5500
Mg^{++}	-	-	-	-	450-550	-	450-550
Na^{+}	-	-	-	-	130-200	-	130-200
K^{+}	-	-	-	-	90-160	-	90-160
Cl^{-}	-	-	-	-	9000-11,000	-	9000-11,000
Corrosion rate of metals,[b] mils/yr							
Aluminum 5005, weld ER1100	-	12, P41	8[c], P16	6[c], Pm	92, P51	< 1	< 1
Armco 22-13-5, weld Armco 22-13-5	< 1	< 1	-	-	< 1	-	-
Brass, red, weld Oxweld 25M	13	1	-	-	21	-	1
Carpenter 20Cb-3, weld Carpenter 20Cb-3	< 1, Pm	< 1, Pm	< 1[c]	1, Pm	< 1	< 1	< 1
Cor-Ten B, weld E8018-C3	-	5	19	17[c]	79	11	7
Crucible 26-1, weld E-Brite 26-1	< 1	-	1[c], P4	-	-	-	-
Cupro-Nickel 70-30, weld B259 RCuNi	1[d]	< 1	4	7	26	< 1	1
E-Brite 26-1, weld E-Brite 26-1	-	< 1, Pm	2[c], P17	1, P9	< 1	< 1	< 1
Hastelloy B, weld Hastelloy B	1	< 1	4	2	13[c]	< 1	1
Hastelloy C-276, weld Hastelloy C-276	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Incoloy 800, weld Inconel 82	-	1, P19	2[c], P8	1, Pm	< 1[e]	< 1	< 1
Incoloy 825, weld Incoloy 65	< 1	< 1	< 1[c], Pm	< 1[c], Pm	< 1	< 1	< 1
Inconel 625, weld Inconel 625	< 1	< 1	< 1	1, Pm	< 1	< 1	< 1
Mild steel, A-283, weld E6012	-	10	26	18[c]	99[c]	12	6
Monel 400, weld Monel 60	1[d]	1	6	2	10[c], Pm	< 1	1[c]
Type 201, weld Type 316	< 1	1, Pm	2[c], P10, -	1[c], Pm, -	1[c], Pm, -	< 1	-
Type 304L, weld Type 308L	-	-	1[c], P17	2[c], Pm	1[c], Pm	< 1	< 1, Pm
Type 316L, weld Type 316L	< 1[e]	< 1	1[e], P9	1, Pm	< 1[c]	< 1	< 1
Type 317, weld Type 317	< 1	< 1	< 1[e]	-	-	-	-
Type 410, weld Type 309	-	-	-	4[c]	-	-	-
Type 446, weld Type 309	-	-	-	2, Pm	-	< 1	< 1[c], P9
USS 18-18-2, weld Inconel 82	-	-	-	3	-	< 1	< 1, Pm
Evaluation of nonmetallic materials[f]							
Bondstrand 4000 (Fiber glass-reinforced epoxy)	-	Good	Poor	-	Good	Good	-
Flakeline 200 (inert flakes and polyester resin)	-	Fair	Fair	Poor	Fair	Good	Fair
Polypropylene	-	-	-	-	-	-	Good
Ceramic							
Transite (Portland cement and asbestos)	-	Good	Good	Good	Good	Good	Good

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[a] The spool of specimens was mounted in the recirculation tank, but the tank was empty throughout the exposure period; this was a test in the atmosphere only; the exposure period was 83 days.

[b] "P" preceeding a number indicates pitting during the exposure period to the depth in mils shown by the number, and "Pm" indicates minute pits.

[c] Crevice corrosion at Teflon insulator.

[d] Attack of weld.

[e] Localized attack of parent metal.

[f] Evaluation: good, little or no change in condition of specimen; fair, definite change—probably could be used; poor, failed or severely damaged.

TABLE IV

Compositions of Alloys Tested in the Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

Alloys	Chemical analysis, %											
	C	Cr	Ni	Fe	Cu	Mo	Mn	Si	P	S	Al	Ti	Others
Aluminum 3003	-	-	-	0.7[a]	0.2	-	1.0-1.5	0.6[a]	-	-	Bal.	-	Zn, 0.1[a]; total 0.15
Armco 22-13-5	0.06[a]	20.5-23.5	11.5-13.5	Bal.	-	1.5-3.0	4.0-6.0	1.0[a]	0.04[a]	0.03[a]	-	-	N, 0.2-0.4; Cb, 0.1-0.3; V, 0.1-0.3
Brass, red	-	-	-	0.05[a]	84-86	-	-	-	-	-	-	-	Zn, Bal.; Pb, 0.05[a]
Carpenter 20Cb-3	0.07[a]	19-21	32-38	Bal.	3-4	2-3	2.00[a]	1.00[a]	0.035[a]	0.035[a]	-	-	Cb+Ta, 8xC
Cor-Ten B[b]	0.066	0.52	0.018	Bal.	0.31	0.010	1.20	0.29	0.012	0.031	0.056	-	V, 0.05
Crucible 26-1	0.02	26	-	Bal.	-	1.0	0.35	0.25	0.025	0.010	-	0.35	N, 0.03
Cupro-Nickel 70-30[b]	-	-	31.00	0.53	67.79	-	0.52	-	0.003	0.005	-	-	Zn, 0.034; Pb, 0.002
E-Brite 26-1[b]	< 0.001	26.17	0.08	Bal.	0.01	1.00	0.01	0.19	0.010	0.012	-	-	N, 0.010
Hastelloy B[b]	< 0.01	0.19	Bal.	5.75	-	26.20	0.55	0.01	0.005	0.006	-	-	Co, 0.35; V, 0.26
Hastelloy C-276[b]	0.002	15.87	Bal.	5.96	-	16.32	0.49	< 0.01	0.012	0.010	-	-	Co, 1.84; W, 3.51; V, 0.25
Incoloy 800[b]	0.04	21.11	31.52	45.01	0.40	-	0.84	0.51	-	0.007	0.48	0.46	-
Incoloy 825[b]	0.04	22.29	42.22	28.30	2.12	-	0.56	0.34	-	0.007	0.06	0.66	-
Inconel 625	0.1[a]	20-23	Bal.	5.00[a]	-	8-10	0.5[a]	0.5[a]	0.015[a]	0.015[a]	0.4[a]	0.4[a]	Co, 1.0[a]; Cb+Ta, 3.15-4.15
Mild Steel, A-283[b]	0.17	-	-	Bal.	0.037	-	0.43	0.070	0.015	0.024	0.005	-	-
Monel 400[b]	0.09	-	64.66	1.00	33.06	-	1.03	0.06	-	0.008	0.004	-	-
Type 201	0.15[a]	16-18	3.5-5.5	Bal.	-	-	5.5-7.5	1.00[a]	0.06[a]	0.03[a]	-	-	N, 0.25[a]
Type 304L	0.03[a]	18-20	8-12	Bal.	-	-	2.00[a]	1.00[a]	0.045[a]	0.03[a]	-	-	-
Type 316L	0.03[a]	16-18	10-14	Bal.	-	2.0-3.0	2.00[a]	1.00[a]	0.045[a]	0.03[a]	-	-	-
Type 317L[b]	0.06	18.6	12.6	Bal.	0.14	3.0	1.3	1.90	0.013	0.010	-	-	-
Type 410[b]	0.062	12.7	0.16	Bal.	0.03	0.054	0.43	0.40	0.014	0.018	0.069	-	N, 0.034; V, < 0.03
Type 446[b]	0.10	24.6	0.50	Bal.	0.045	0.10	0.71	0.37	0.018	0.010	0.008	< 0.02	N, 0.19; V, < 0.03
USS 18-18-2[b]	0.065	18.2	18.0	Bal.	0.03	0.013	1.50	1.94	0.007	0.009	0.001	-	N, 0.04

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[a] Maximum.

[b] Analysis was supplied with the material received for use in corrosion tests.

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TABLE V

Analyses[a] of Deposits in Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

Identification of sample			Composition, % by weight						
Date	Number	Location	CaO	$CaSO_3$	$CaSO_4$	$CaCO_3$	MgO	Others	Acid insoluble
Venturi System									
8/17/73	VD-1	1/64-inch solids from wall of flooded elbow	-	19.27	17.07	3.60	0.44	-	60.06
8/20/73	VD-1	20-mil scale from spray header in bottom of afterscrubber	-	5.28	73.71	0.10	0.047	-	20.45
9/10/73	VD-1	Solids from top of demister	-	27.29	15.54	12.29	0.21	-	44.37
8/14/73	VD-1	Light-colored deposit from top spray at demister	-	27.87	44.25	0.70	0.007	-	27.21
9/10/73	VD-2	Solids from scrubber outlet at 40-inch stainless steel duct	-	Trace	40.44	0.17	0.018	-	59.33
8/29/73	VD-1	Solids from scrubber outlet at 40-inch stainless steel duct	-	3.40	60.76	0.35	0.04	-	35.48
9/10/73	VD-5	Material from crack in stack below bellows joint	-	11.95	45.20	0.44	0.75	-	41.64
9/10/73	VD-4	Solids from TE-1015 at reheater discharge	-	47.82	25.48	3.48	0.90	-	23.22
8/13/73	VD-1	Solids from above the reheater	-	-	-	-	-	Cl, 11.6	-
9/10/73	VD-5	Wet, black solids from ID fan discharge duct	-	3.02	70.39	0.199	1.21	(Probably carbonaceous)	25.17
TCA System									
8/15/73	No. 7	Deposit from inlet flue-gas duct near soot blower	-	35.90	32.50	9.75	0.004	-	22.20
8/15/73	No. 6	Deposit from bottom (first) grid	24.31	3.39	71.71	0.43	0.013	-	0.13
8/13/73	No. 3	Deposit from door at elevation of 3'6 feet	26.03	24.01	27.76	5.3	0.058	-	16.14
8/13/73	No. 1	Deposit from wash tray weir	25.29	2.56	58.47	Trace	0.022	-	13.67
8/13/73	No. 2	Deposit from wall between wash tray and demister	25.63	1.60	60.39	Trace	0.022	-	12.36
8/14/73	No. 5	Deposit from bottom of demister	-	0.44	50.87	0.27	0.014	-	43.68
8/14/73	No. 4	Deposit from 40-inch duct at reheater outlet	-	1.13	53.48	0.3	1.16	-	45.52
9/7/73	PHD-1	Deposit in the line to pH meter AP-226	-	5.47	50.16	19.36	0.32	-	24.70
9/17/73	TCAD-1	Deposit from strainer in tank D-204	-	9.62	51.99	Trace	0.11	-	37.96

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[a] Information taken from reports by J. B. Barkley to P. E. Stone and/or J. K. Metcalfe during the period 8/16/73 to 9/18/73.

TABLE VI

Hardness of Neoprene Linings of Equipment in the Three Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Exposure period: 6/5 to 9/16/73--dates inclusive for the three systems)

Location of hardness test	Durometer "A" hardness		
	Original[a]	Current[b]	At °F[c]
Venturi System (1516 operating hours)			
After-Scrubber Tower:			
Eight inches below Type 316L S.S. at venturi section	60-65	58-61	61
Sidewalls near cone-shaped bottom (approx. elevation, 571 feet)	60-65	53-62	61
At approximate elevation, 587 feet	60-65	54-60	57
At approximate elevation, 592 feet	60-65	52-56	57
Three inches below mist eliminator (approx. elevation, 598 feet)	60-65	54-59	55
Three feet above mist eliminator (approx. elevation, 403 feet)	60-65	46-50	55
Recirculation Tank, D-104:			
Five feet above bottom	55-60	65-72	73
Blades of agitator	60-70	66-71	73
Clarified Process Water Storage Tank, D-103:			
Above liquid level	55-60	67-72	54
Below liquid level	55-60	67-72	54
Reslurry Tank, D-403:			
Above liquid level	-	65-71	55
Blades of Agitator In:			
Effluent hold tank, D-101	60-70	58-64	73
TCA System (1861 operating hours)			
Scrubber Tower:			
Four inches above inlet gas duct (approx. elevation, 376 feet)	60-65	55-62	68
Six inches above bottom grid (approx. elevation, 380 feet)	60-65	57-62	72
Three feet above the second grid, near Test 2006 (approx. elevation, 386 feet)	60-65	57-61	72
Four feet below Koch tray (approx. elevation, 398 feet)	60-65	55-61	72
Two feet above Koch tray (approx. elevation, 404 feet)	60-65	45-53	72
Six inches below S.S. duct to reheater (approx. elevation, 408 feet)	60-65	53-65	72
Recirculation Tank, D-204:			
Five feet above bottom	55-60	59-67	73
Blades of agitator	60-70	53-56	73
Clarified Process Water Storage Tank, D-203:			
Above liquid level	55-60	62-70	55
Below liquid level	55-60	68-73	55
Blades of Agitator In:			
Effluent hold tank, D-201	60-70	65-70	73
Pumps:			
Impeller G-201, G-202, G-203, G-205	54-56	59-67	73
Liner G-201, G-202, G-203, G-205	54-56	-	73
Impeller G-206	54-56	51-55	73
Liner G-206	54-56	51-55	73
Marble-Bed System (431 operating hours)			
Scrubber Tower:			
Five inches above bottom cone (approx. elevation, 370 feet)	60-65	66-73	68
Six inches above marble bed (approx. elevation, 377 feet)	60-65	67-75	68
Above demister and 6 inches below reducer (approx. elevation, 383 feet)	60-65	66-72	68
Three inches below S.S. 40-inch stack (approx. elevation, 385 feet)	60-65	66-75	68
Recirculation Tank, D-304:			
Five feet above bottom	55-60	62-67	73
Blades of agitator	60-70	70-73	73
Clarified Process Water Storage Tank, D-303:			
Above liquid level	55-60	64-72	55
Below liquid level	55-60	64-72	55
Bottom of tank under impeller	55-60	69-73	55
Blades of agitator In:			
Effluent hold tank, D-301	60-70	62-70	73

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[a] Values not determined by TVA but were taken from information supplied to contractors for bidding on construction.

[b] The instrument used to determine the durometer hardness of neoprene linings during inspection of the plants (Sept. 18-20, 1973) was Shore "A2," ASTM D2240. Note that the measurements were made over a wide range of temperatures; therefore, an exact comparison of hardness values is not possible. Usually three or more tests were made in an area.

[c] The atmospheric temperature varied from about 55° to 73°F while tests for hardness were being made.

TABLE VII

Compilation of Corrosion Data of Materials Tested in the Three Limestone - Wet-Scrubbing Systems for Sulfur Dioxide Removal from Stack Gas at Shawnee Power Plant

(Test period, inclusive: June 5 to September 16, 1973)

Alloy	No. of specimens tested	Corrosion[a] On basis of wt. loss,[c] mils/yr	Specimens pitted[b] No.	Depth, mils Min.	Depth, mils Max.	Specimens with crevice attack, No.	Specimens with other types of attack No.	Identification
Aluminum 5005	17	< 1-92	9	M	84	6	2	1^d, 1^e
Armco 22-13-5	9	< 1	0	0	0	0	1	1^f
Brass, red	10	1-21	0	0	0	0	4	1^d, 2^e, 1^f
Carpenter 20Cb-3	23	< 1-2	6	M	18	3	2	1^d, 1^f
Cor-Ten B	19	< 1-79	2	M	3	3	3	1^d, 1^f, 1^g
Crucible 26-1	7	< 1-1	3	4	14	4	1	1^f
Cupro Nickel 70-30	23	< 1-71	0	0	0	0	4	1^d, 1^e, 2^h
E-Brite 26-1	20	< 1-2	11	M	24	7	1	1^d
Hastelloy B	23	< 1-13	1	0	M	1	2	1^d, 1^f
Hastelloy C-276	23	< 1	0	0	0	0	1	1^f
Incoloy 800	20	< 1-21	13	M	22	9	1	1^i
Incoloy 825	23	< 1-2	3	M	7	7	2	1^d, 1^f
Inconel 625	23	< 1-1	1	0	M	0	2	1^d, 1^f
Mild steel, A-283	20	< 1-122	4	M	9	5	2	1^d, 1^f
Monel 400	23	< 1-33	1	0	M	3	7	$1^{d,e}$, 4^e, $1^{e,h}$, 1^f
Type 201	14	< 1-15	10	M	29	7	3	1^d, 1^f, 1^i
Type 304L	19	< 1-17	14	M	20	11	1	1^d
Type 316L	23	< 1-7	7	M	11	8	3	1^d, $1^{f,i}$, 1^i
Type 317	8	< 1-1	1	0	8	3	2	1^d, 1^f
Type 410	10	< 1-21	8	M	20	8	1	1^d
Type 446	14	< 1-17	12	M	30	9	0	0
USS 18-18-2	16	< 1-18	11	M	25	10	1	1^d

Evaluation of nonmetallic materials[j]	Condition Good	Fair	Poor
Bondstrand 4000 (fiber glass reinforced epoxy)	11	3	3
Flakeline 200 (inert flakes and polyester resin)	1	15	2
Lucoflex, polyvinyl chloride . . .	0	0	1
Polyethylene Type III (high density)	0	0	1
Polypropylene	2	0	1
Ceramic			
Transite (Portland cement and asbestos)	15	2	2

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[a] Tables I, II, and III give corrosion data for the materials tested in the venturi, the TCA, and the marble-bed scrubber systems, respectively. Because the number of specimens tested of alloys ranged from 7 to 23, an order of decreasing corrosion resistance could not be established.

[b] M, minute pit; the numerical values show the actual depth of penetration in mils during test period.

[c] The range of corrosion rates does not include severe abrasion which is identified under "other types of attack."

[d] Specimen worn by movement of plastic balls at test location 2006.

[e] Attack of weld.

[f] Erosion and corrosion of specimen at test location 1011.

[g] Attack of heat-affected zone of weld.

[h] Denickelification.

[i] Localized attack of parent metal.

[j] Evaluation: good, little or no change in condition of specimen; fair, definite change—probably could be used; poor, failed or severely damaged.

TABLE VIII

Cost of Alloys Tested in the Three Limestone - Wet-Scrubbing Systems for Removal of Sulfur Dioxide from Stack Gases at the Shawnee Power Plant

(Test period inclusive: June 5 to Sept. 16, 1973)

	Cost ratio[a]				
	3/4-inch tubing		1/8-inch sheet		
Source of information[b]:	A	B	B	C	D
Aluminum 3003	-	0.85	0.79	0.79	-
Armco 22-13-5	-	-	-	-	-
Brass, red	-	-	2.99	2.99	-
Carpenter 20Cb-3	4.21	-	-	3.73	-
Cor-Ten B	-	-	-	-	0.22
Crucible 26-1	-	-	-	-	1.66
Cupro-Nickel 70-30	1.80[c]	-	-	-	2.28
E-Brite 26-1	-	-	-	1.85	-
Hastelloy B	9.47	-	-	-	-
Hastelloy C-276	9.29	-	-	-	-
Incoloy 800	2.54	-	-	2.70	2.86
Incoloy 825	4.46[c]	-	-	3.73	-
Inconel 625	6.59[d]	-	-	6.05	-
Mild steel, A-283	0.34[d], 0.80[c]	-	-		0.19
Monel 400	2.93[d]	-	-	3.61	3.45
Type 201	-	-	-	-	-
Type 304L	1.11	-	-	1.11	-
Type 316L	1.39		-	1.61	1.66
Type 317	1.80	-	-	-	
Type 410	1.92	-	-	-	-
Type 446	-	-	-	-	-
USS 18-18-2	-	-	-	-	-

---

[a] Cost ratio values (as of reference date) are based on Type 304 stainless steel having a value of 1.00. The ratios are for commercial quality 3/4-inch tubing of 0.065-inch wall which is cut to 20-foot 0-inch lengths and quantity of 10,000 feet or for (approx.) 1/8-inch sheet in 20,000-pound lots.

[b] A, Carpenter Technology Corporation, August 7, 1973.
B, J. M. Tull, Birmingham, Alabama, by telephone March 8, 1974.
C, J. M. Tull, Atlanta, Georgia, by telephone July 2, 1973.
D, Crucible Stainless Steel Division, Colt Industries, Pittsburgh, Pennsylvania, from a representative visiting at TVA February 22, 1973.

[c] Seamless.

[d] Welded.

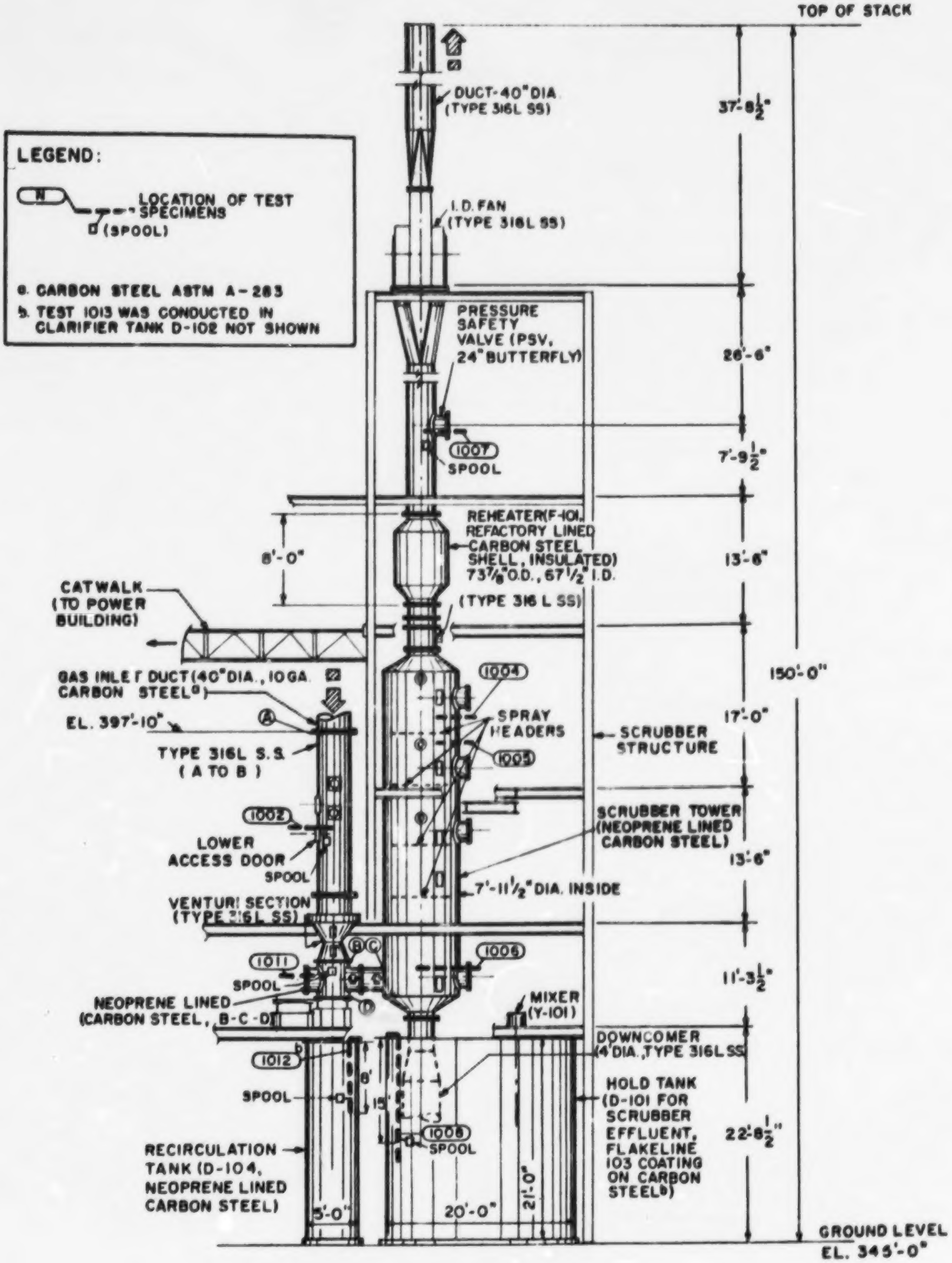
LEGEND:
N
LOCATION OF TEST SPECIMENS
(SPOOL)
a. CARBON STEEL ASTM A-283
b. TEST 1013 WAS CONDUCTED IN CLARIFIER TANK D-102 NOT SHOWN
TOP OF STACK
DUCT-40" DIA. (TYPE 316L SS)
37'-8½"
I.D. FAN (TYPE 316L SS)
PRESSURE SAFETY VALVE (PSV, 24" BUTTERFLY)
26'-6"
1007
SPOOL
7'-9½"
REHEATER (F-101, REFRACTORY LINED CARBON STEEL SHELL, INSULATED) 73⅞" O.D., 67½" I.D.
8'-0"
13'-6"
(TYPE 316 L SS)
CATWALK (TO POWER BUILDING)
GAS INLET DUCT (40" DIA., 10 GA. CARBON STEELa)
EL. 397'-10"
A
1004
SPRAY HEADERS
1005
SCRUBBER STRUCTURE
17'-0"
150'-0"
TYPE 316L S.S. (A TO B)
1002
LOWER ACCESS DOOR
SPOOL
SCRUBBER TOWER (NEOPRENE LINED CARBON STEEL)
13'-6"
7'-11½" DIA. INSIDE
VENTURI SECTION (TYPE 316L SS)
B
C
1011
SPOOL
1006
11'-3½"
D
NEOPRENE LINED (CARBON STEEL, B-C-D)
MIXER (Y-101)
DOWNCOMER (4' DIA., TYPE 316L SS)
1012
8'
15'
SPOOL
1008
SPOOL
HOLD TANK (D-101 FOR SCRUBBER EFFLUENT, FLAKELINE 103 COATING ON CARBON STEELb)
22'-8½"
RECIRCULATION TANK (D-104, NEOPRENE LINED CARBON STEEL)
5'-0"
20'-0"
21'-0"
GROUND LEVEL EL. 345'-0"

FIGURE 1

VENTURI SCRUBBER SYSTEM (C-101)

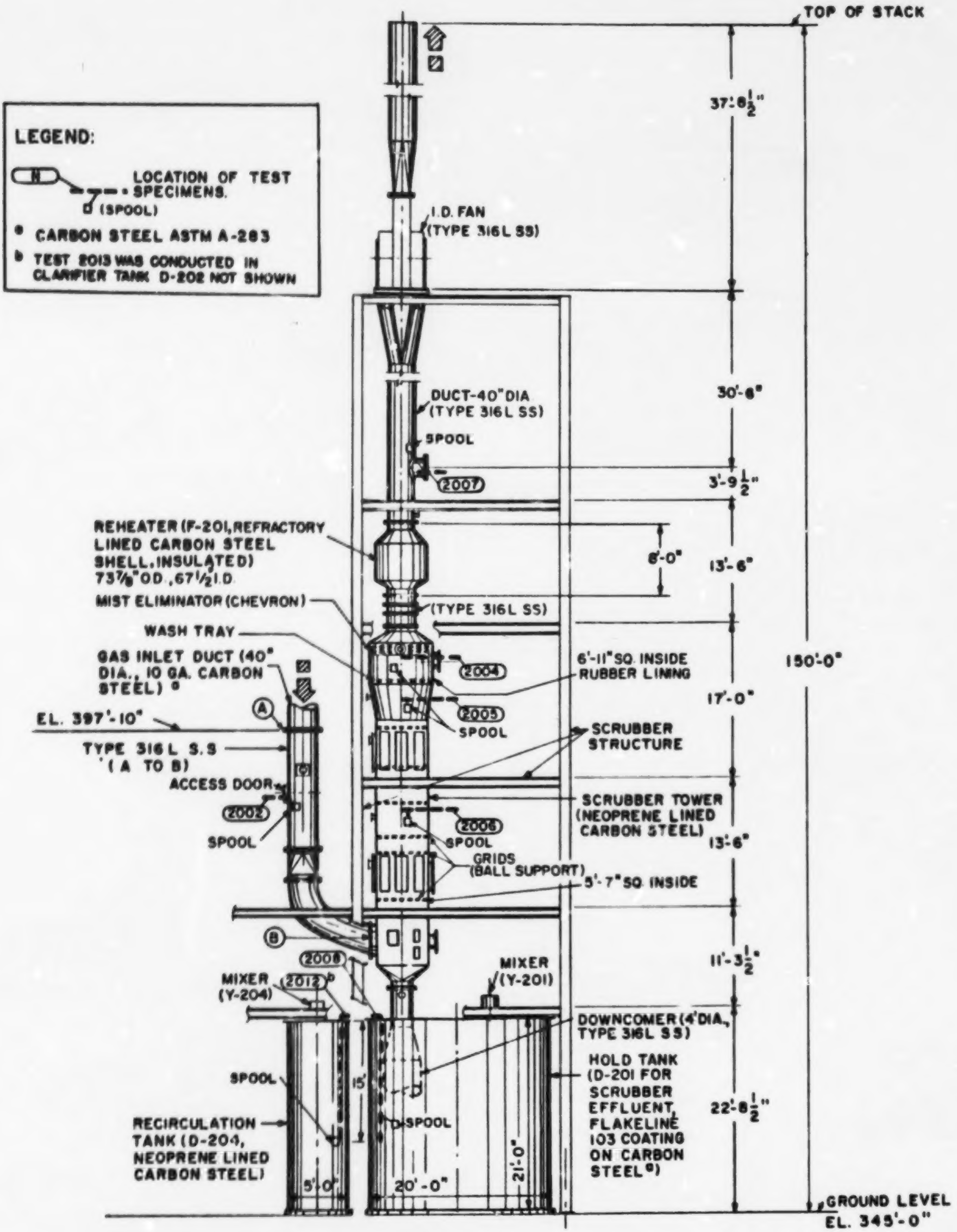
TOP OF STACK
LEGEND:
N LOCATION OF TEST SPECIMENS.
(SPOOL)
a CARBON STEEL ASTM A-283
b TEST 2013 WAS CONDUCTED IN CLARIFIER TANK D-202 NOT SHOWN
I.D. FAN (TYPE 316L SS)
37'-6 1/2"
DUCT-40" DIA (TYPE 316L SS)
SPOOL
2007
30'-6"
3'-9 1/2"
REHEATER (F-201, REFRACTORY LINED CARBON STEEL SHELL, INSULATED) 73 7/8" OD., 67 1/2 I.D.
8'-0"
13'-6"
MIST ELIMINATOR (CHEVRON)
(TYPE 316L SS)
WASH TRAY
GAS INLET DUCT (40" DIA., 10 GA. CARBON STEEL) a
2004
6'-11" SQ. INSIDE RUBBER LINING
2005
SPOOL
17'-0"
150'-0"
EL. 397'-10"
A
TYPE 316L S.S (A TO B)
SCRUBBER STRUCTURE
ACCESS DOOR
2002
SPOOL
SCRUBBER TOWER (NEOPRENE LINED CARBON STEEL)
2006
SPOOL
GRIDS (BALL SUPPORT)
13'-6"
5'-7" SQ. INSIDE
B
2008
MIXER (Y-204)
2012 b
MIXER (Y-201)
11'-3 1/2"
DOWNCOMER (4' DIA, TYPE 316L SS)
SPOOL
15'
HOLD TANK (D-201 FOR SCRUBBER EFFLUENT, FLAKELINE 103 COATING ON CARBON STEEL a)
22'-8 1/2"
SPOOL
RECIRCULATION TANK (D-204, NEOPRENE LINED CARBON STEEL)
21'-0"
5'-0"
20'-0"
GROUND LEVEL EL. 345'-0"

FIGURE 2

TURBULENT CONTACT SCRUBBER SYSTEM, TCA-(C-201)
(MOBILE BED — PING-PONG BALL)

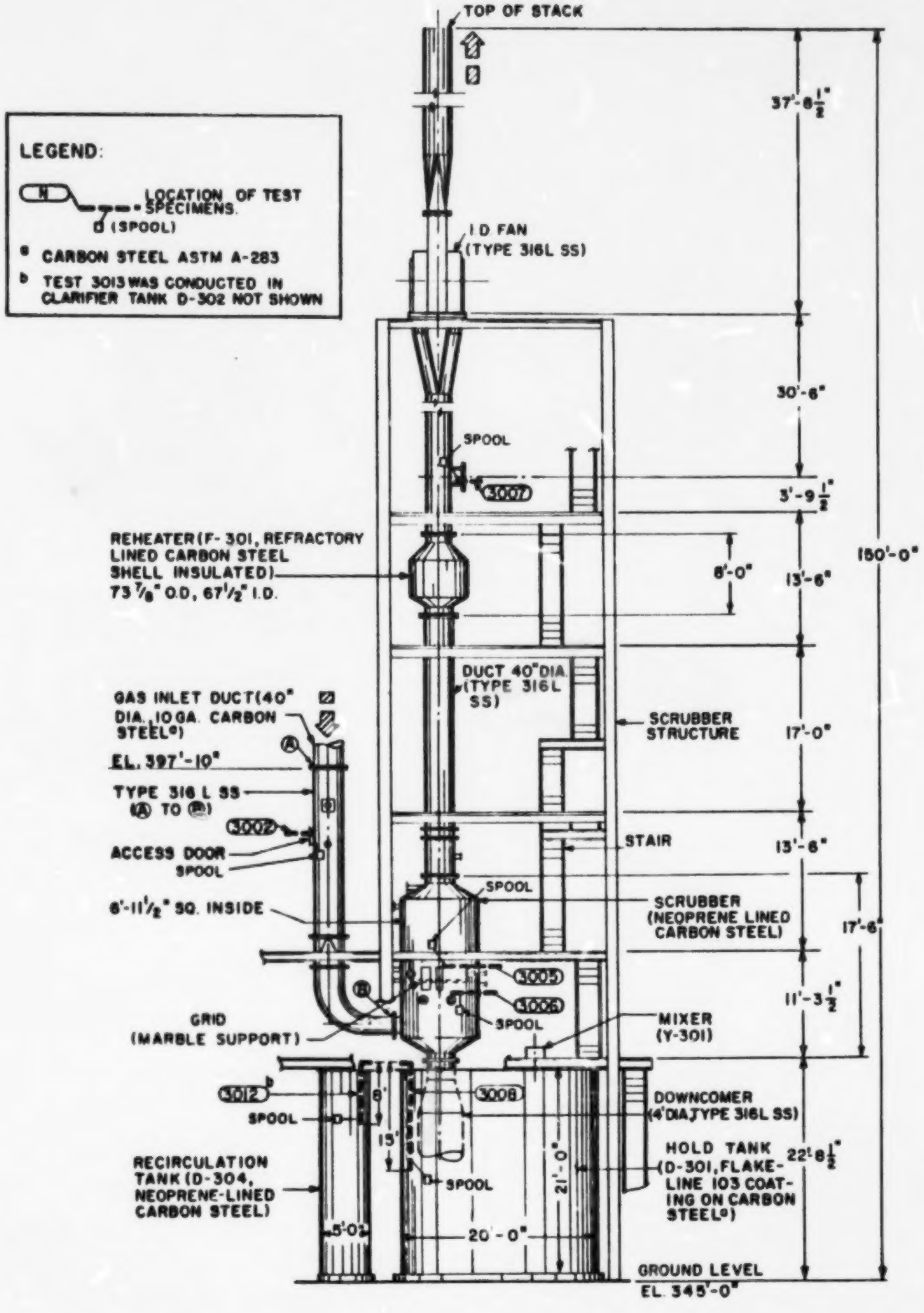
LEGEND:
LOCATION OF TEST SPECIMENS.
(SPOOL)
a CARBON STEEL ASTM A-283
b TEST 3013 WAS CONDUCTED IN CLARIFIER TANK D-302 NOT SHOWN
TOP OF STACK
37'-8 1/2"
I.D. FAN (TYPE 316L SS)
30'-6"
SPOOL
3007
3'-9 1/2"
REHEATER (F-301, REFRACTORY LINED CARBON STEEL SHELL INSULATED) 73 7/8" O.D, 67 1/2" I.D.
8'-0"
13'-6"
150'-0"
DUCT 40" DIA. (TYPE 316L SS)
GAS INLET DUCT (40" DIA. 10 GA. CARBON STEEL a)
A
EL. 397'-10"
SCRUBBER STRUCTURE
17'-0"
TYPE 316 L SS (A TO B)
3002
ACCESS DOOR
SPOOL
STAIR
13'-6"
SPOOL
6'-11 1/2" SQ. INSIDE
SCRUBBER (NEOPRENE LINED CARBON STEEL)
17'-6"
3005
B
3006
11'-3 1/2"
SPOOL
GRID (MARBLE SUPPORT)
MIXER (Y-301)
3012 b
8'
3008
SPOOL
DOWNCOMER (4' DIA. TYPE 316L SS)
15'
HOLD TANK (D-301, FLAKE-LINE 103 COATING ON CARBON STEEL a)
22'-8 1/2"
21'-0"
SPOOL
RECIRCULATION TANK (D-304, NEOPRENE-LINED CARBON STEEL)
5'-0"
20'-0"
GROUND LEVEL
EL. 345'-0"

FIGURE 3

MARBLE-BED SCRUBBER SYSTEM, MB-(C-301)

(FLOODED BED OF MARBLES)

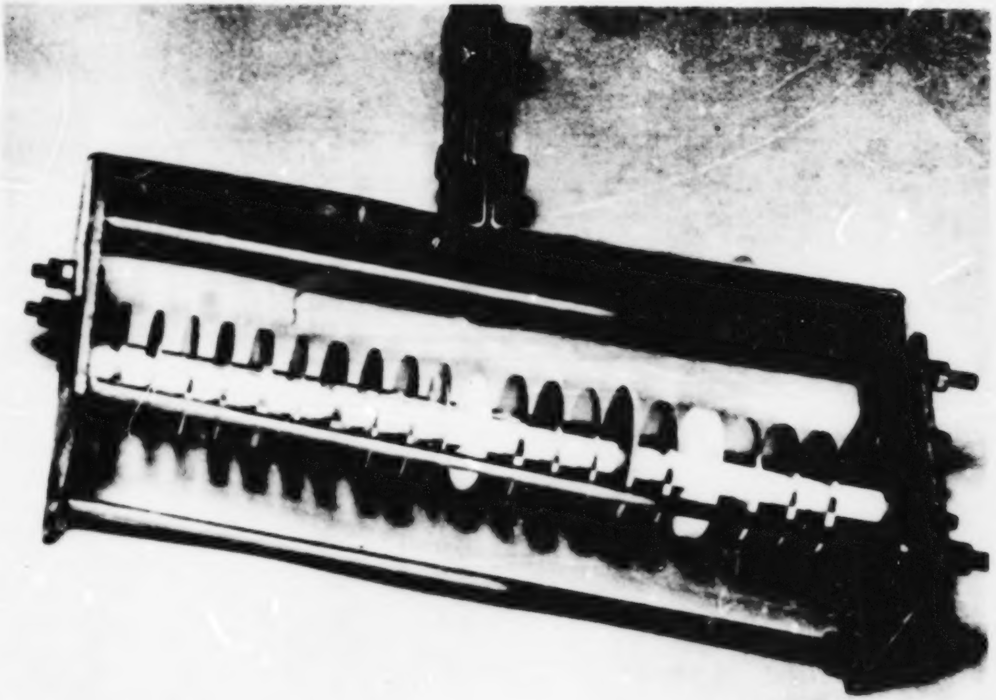

FIGURE 4
TYPICAL SPOOL ASSEMBLY OF CORROSION TEST SPECIMENS
(2-INCH DISKS)

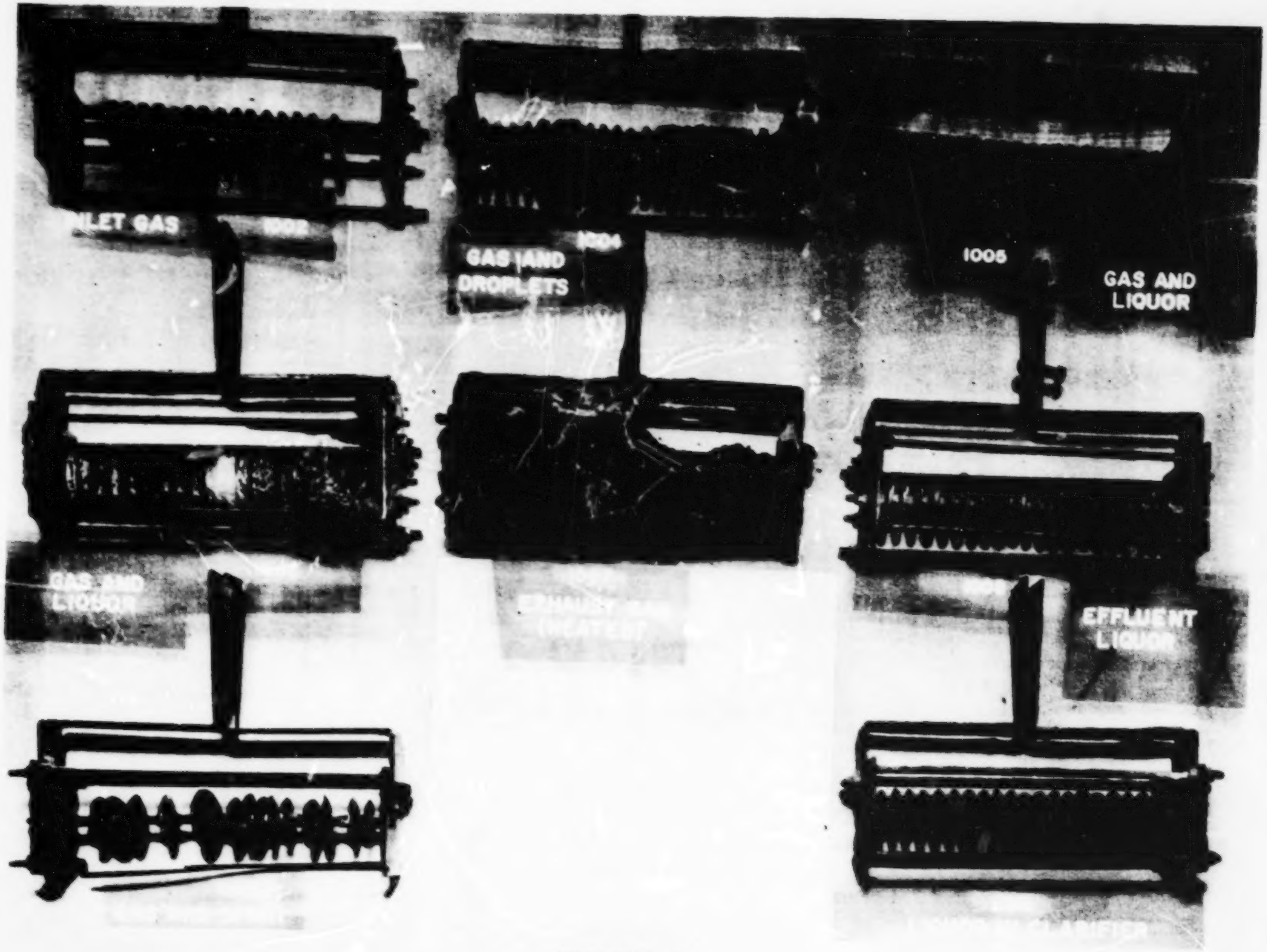

FIGURE 5
DISK SPECIMENS AFTER EXPOSURE IN VENTURI SYSTEM (JUNE 13 - SEPT. 16, 1973)

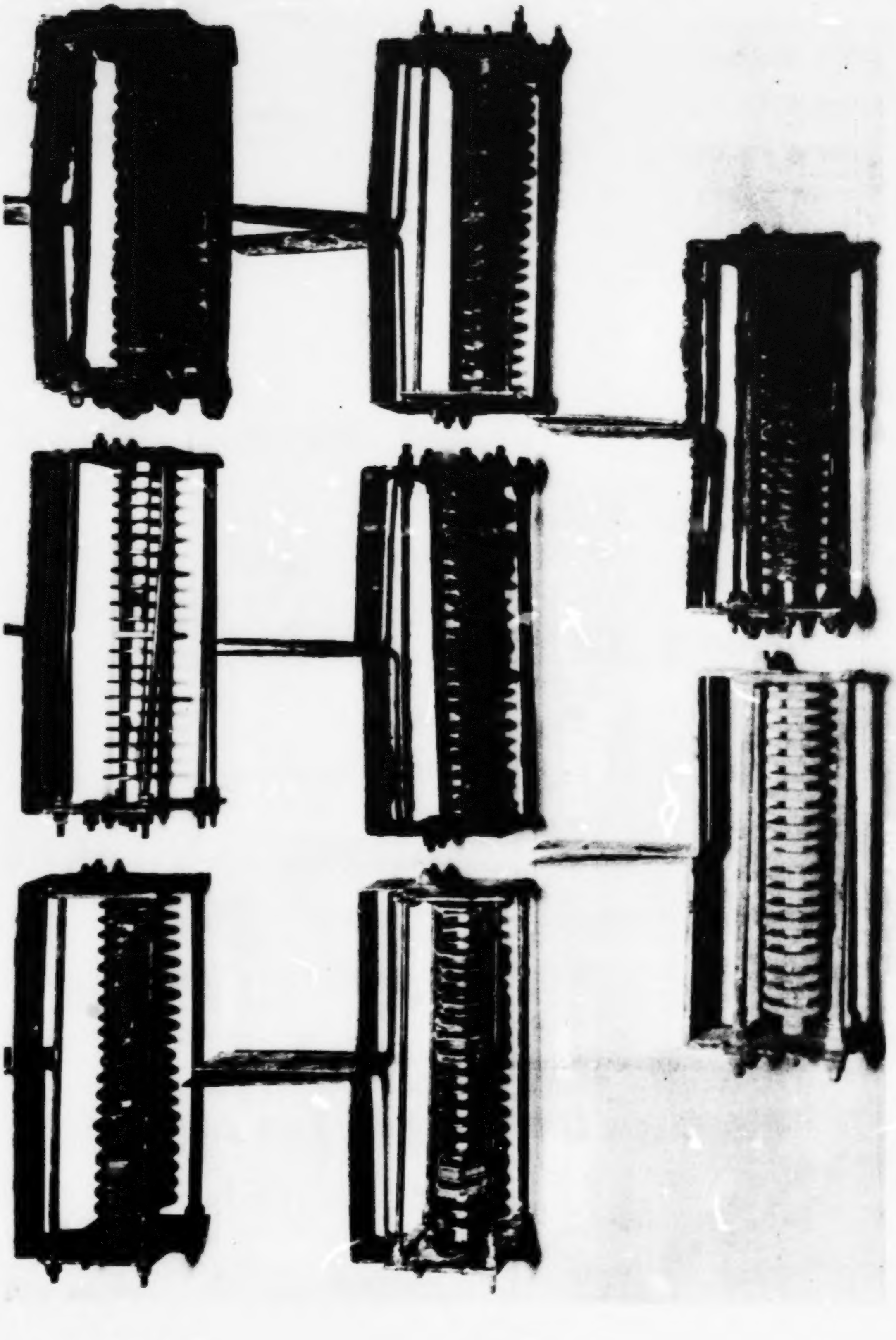

FIGURE 6

DISK SPECIMENS AFTER EXPOSURE IN TCA SYSTEM (JUNE 5-SEPT. 14, 1973)

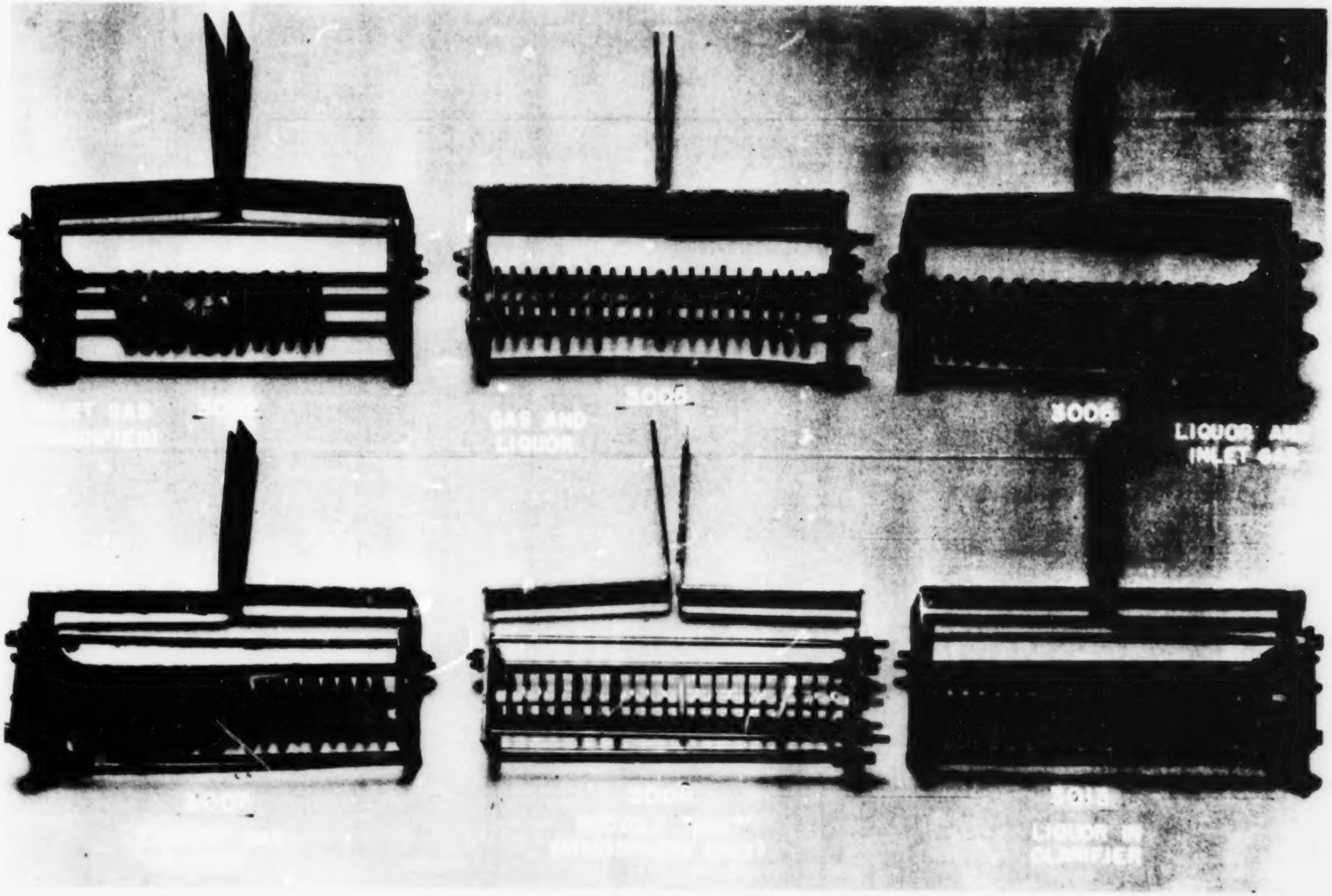

FIGURE 7

DISK SPECIMENS AFTER EXPOSURE IN MARBLE-BED SYSTEM (JUNE 8 - AUG. 30, 1973)

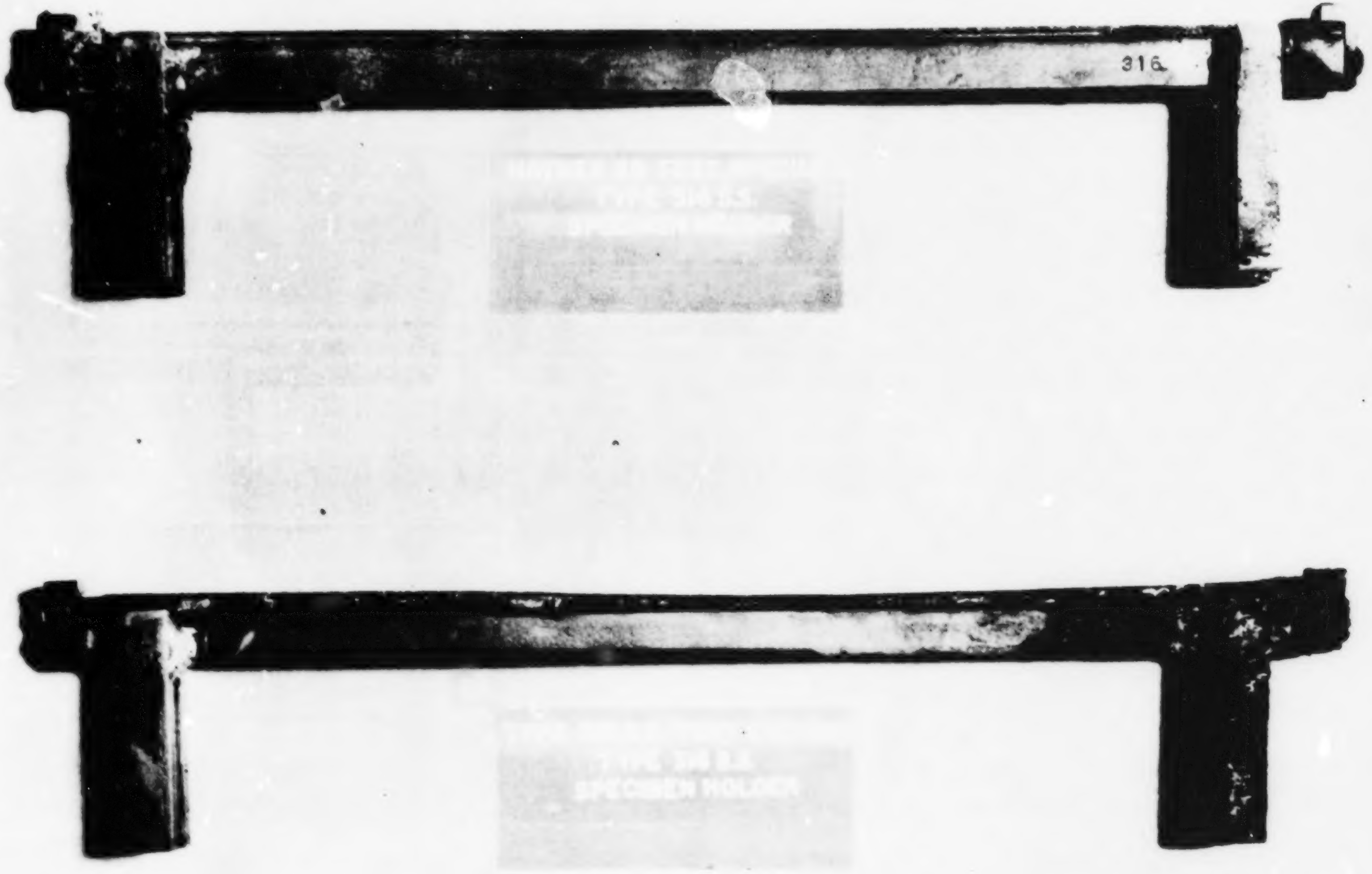

FIGURE 8

WEAR- BAR TEST ASSEMBLIES EXPOSED ON THE SLIDING GUIDES AT THE VENTURI CONE NOZZLE (AUG. 29-SEPT. 16, 1973)

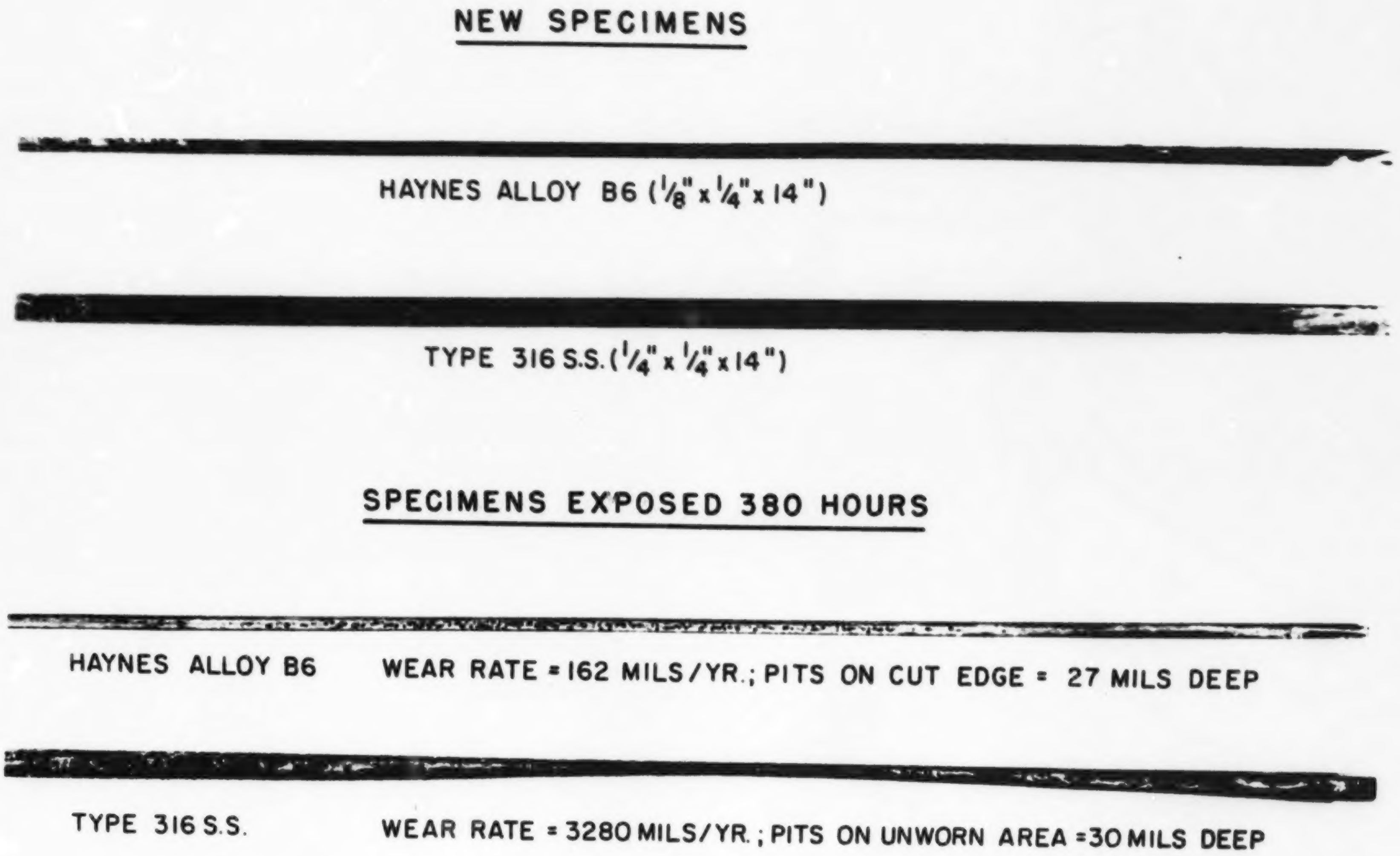
NEW SPECIMENS
HAYNES ALLOY B6 (1/8" x 1/4" x 14")
TYPE 316 S.S. (1/4" x 1/4" x 14")
SPECIMENS EXPOSED 380 HOURS
HAYNES ALLOY B6
WEAR RATE = 162 MILS/YR.; PITS ON CUT EDGE = 27 MILS DEEP
TYPE 316 S.S.
WEAR RATE = 3280 MILS/YR.; PITS ON UNWORN AREA = 30 MILS DEEP

FIGURE 9
NEW AND EXPOSED WEAR-BAR SPECIMENS FOR TESTING IN THE VENTURI CONE NOZZLE

Appendix L

DEFINITION OF STATISTICAL TERMS

The fraction of variation that is explained by a correlation is equal to R^2, where R is the correlation coefficient. Thus (Ref 7, P 175):

$$\text{Fraction of Variation Explained} = R^2 = 1 - \frac{\Sigma (y - y')^2}{\Sigma (y - \bar{y})^2} \qquad \text{(L-1)}$$

where:

y = value of the independent variable for a particular data point

y' = predicted (correlation) value of the independent variable for the same data point

$\bar{y}$ = arithmetic average of all values of the independent variable in the correlated set of data

The standard error of estimate is determined from the following equation (Ref 7, P 174):

$$\text{Standard Error of Estimate} = \sqrt{\frac{\Sigma (y - y')^2}{n - k - 1}} \qquad \text{(L-2)}$$

where:

n = number of data points in the correlated set of data

k = number of dependent variables fitted with coefficients